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Report No. IITRI-C6206-12
(Final Engineering Report)

FURTHER DEVELOPMENT OF THE ROTATING BRUSH AEROSOL SEPARATOR

January 8, 1970 through October 7, 1970

Contract No. N00019-70-C-0256
IITRI Project C6206

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FOREWORD

ROTATING BRUSH AEROSOL SEPARATOR

This final report presents the results obtained during development work on Contract No. N00019-70-C-0256 for the Naval Air Systems Command. The purpose of the program was to further develop and test the rotating brush aerosol separator to the point where an airframe manufacturer could intelligently design a separator for protection of specific helicopter turbines. The program started January 1970 and all planned experimental work was completed in November 1970.

Respectfully submitted,

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ABSTRACT

ROTATING BRUSH AEROSOL SEPARATOR

The rotating brush aerosol separator developed on Contract No. N00019-68-C-0459 was redesigned and extensively modified to permit a parametric investigation of the design and operational variables. Centrifugal effects ~~have been~~ found to be an important mechanism, although impaction effects significantly enhance separation at brush speeds above 2400 RPM. In comparable tests with flat-blades versus 1 mm wires, the wire brushes required 15% less horsepower at 3000 RPM and 8000 CFM to achieve a 95% separation efficiency compared to 86% for the flat-blade brushes. The highest efficiencies were obtained with the near exhaust position when the wire brush speeds exceeded 2400 RPM. The addition of wires in the axial direction (more or longer brushes) is more efficient than in the radial direction (more wires/row), especially for the 2 mm wires. Similarly, at 3000 RPM and 8000 CFM when the number brushes was doubled, the amount of dust which was not removed by the separator was reduced by one-half. While the 1 mm wires appear to be more efficient than the 2 mm wires on a constant impaction area basis, considerations of wire erosion and ease of maintenance favors the use of the heavier wires.

Separation efficiencies at 8000 CFM and 3000 RPM approached 100% for size-classified test dusts in the 15-35 μm size range. At 2.7 μm, the separation efficiency had fallen to a respectable 66%. Above 35 μm, the separation efficiency on the sodium bicarbonate test dust appears to drop away somewhat from 100%, perhaps due to some large particle size reduction by impact with brush wires. Only 7 HP was required to rotate the brush shaft at 3000 RPM and 8000 CFM and at a pressure drop of only four inches of water.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF FIGURES (Cont'd)

ROTATING BRUSH AEROSOL SEPARATOR

I. INTRODUCTION

This program was directed toward the continuing development of a rotating brush aerosol separator. The previous program, Contract No. N00019-68-C-0459, demonstrated the feasibility of the rotating brush dust separator for use as an air cleaning device for protecting helicopter turbine engines from ingestion of abrasive dust without an excessive power or performance penalty. Extrapolation of data taken at low-inlet air volumes clearly showed that an efficiency of more than 90% could be achieved on a 45-micron mass median diameter dust with an expenditure of but 7 HP per 10,000 CFM of cleaned air.

The principle of operation of the rotating brush aerosol separator is the fact that particle impaction theory predicts that the smaller the diameter of the collecting surface, in this case, a wire or filament, the greater the efficiency of the collector in sweeping out small particles in its path. Thus, a rotating brush composed of many fine filaments should be effective in impacting and scavenging particles ingested into an airstream. The British Admiralty Research Laboratory[1,2,3,4] first reported the theoretical development of the rotating brush separator. The theoretical studies in Great Britain predicted efficient contact between the dust particles and the brush filaments, but the behavior of the dust particles after impaction was open to question. The suggestion was made that solid particles could be kept from being re-entrained by wetting the filaments with a water spray.

The previous program at IIT Research Institute[5] demonstrated that high collection efficiencies could be obtained without the use of wetted brush filaments. The introduction of a water spray into a turbine inlet would be undesirable for several reasons, and would require an on-board water supply of considerable capacity in view of the enormous volume of air handled during a typical day's operation, even if one only considers water injection during landing and take-off. The relative effectiveness of impaction and centrifugal forces in the operation of the brush separator was not clear, and one of the objectives of the current program is to clarify this point. Separation of dust in the brush separator may result from centrifugal forces alone, i.e., the rotating brush may impart enough spin to the air-stream to cause the particles to drift to the periphery under the influence of centrifugal forces. Impaction on the filaments may appreciably increase the residence time of the particles in the collection zone by trapping them in the turbulent eddies of the rotating filaments.

Besides establishing the relative importance of impaction and centrifugal effects, the purpose of this program is to generate sufficient design and operating data to enable an airframe manufacturer to plan and fabricate brush engine air particle separators for use on specific helicopter turbine air inlets.

II. EXPERIMENTAL PROCEDURES

A. Brush Separator and Test Facility

The schematic for the experimental brush separator and test facility is shown in Fig. 1, and is essentially the same as that used previously in the prior program, except for improvements in the introduction of dust and in the sampling probes. Air outside the Chemistry Research Building at the third floor level is drawn through a duct with a Lau Blower Model A20-20K driven 1230 RPM by a 25 HP motor. The main airstream then passes through the brush separator and is exhausted to the outside of the building through another duct. A removable orifice plate downstream of the separator controls the air flowrate. A Vickers Model MFB-5-UY-20 hydraulic motor drives the rotating brush to speeds as high as 3000 RPM.

The conduct of the tests, as outlined in the proposal, necessitated a redesign of the brush assemblies to permit the use of 1 mm wires, 2 mm wires, and flat-blades. Also, since the original brushes had 25 wire mounting rods, operation with one-half of the rods was not possible; therefore, the redesigned brushes have 24 wire mounting rods so that either 12 or 24 rods could be used in a balanced assembly. The use of the thicker wires and the heavy flat-blades made necessary the use of thicker rods and a slightly larger brush hub to accommodate the thicker rods around the circumference of the hub.

The use of four brushes instead of the three used previously also required a housing modification and a change in the supports and the shaft rear bearing location.

Operation of the separator with a variable downstream location for the annular exhaust outlet was also included in the redesign of the portion of the separator downstream of the rotating brushes.

Drawings of the modified brush separator components, including an assembly drawing, are shown in Appendix A.

A 10 HP hydraulic power unit was used to permit operation of the brush at 3000 RPM for high CFM throughputs. In previous tests, 2100 RPM was highest brush speed possible; and at the highest CFM throughput of 8000 CFM, 1800 RPM was the highest brush speed attainable. The higher brush speeds used improved separation efficiency significantly.

A single brush assembly using 1 mm wires is shown in Fig. 2. A flat-blade brush assembly, Fig. 3, was used in tests comparing centrifugal and impaction mechanisms. Figure 4 shows three brushes mounted on a shaft with spaces between them as was used in the previous test program. In the current test program covered in this report, the spacers were omitted so that as many as four brushes could be mounted on the drive shaft. The interior of the brush

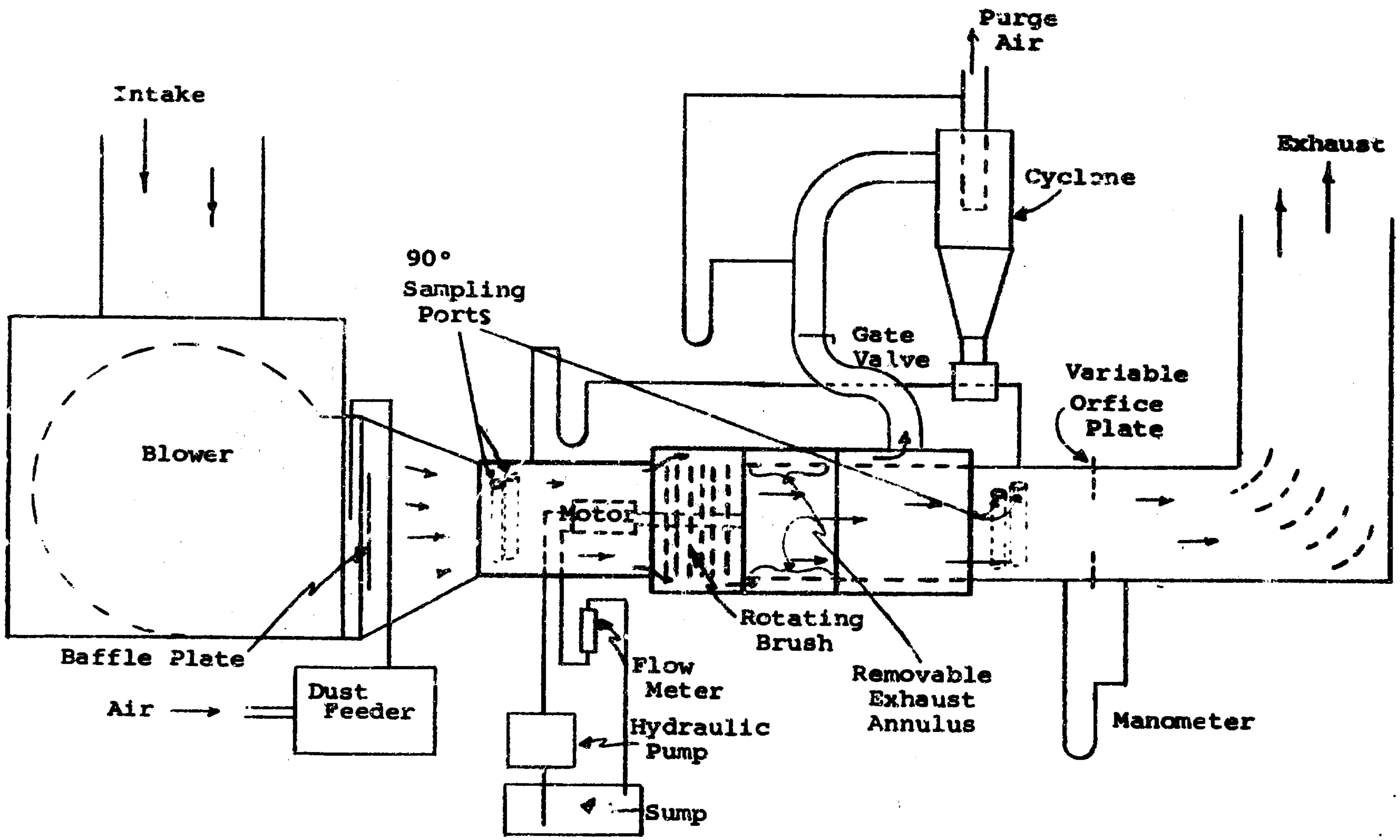

Figure 1: BRUSH SEPARATOR AND TEST FACILITY SCHEMATIC

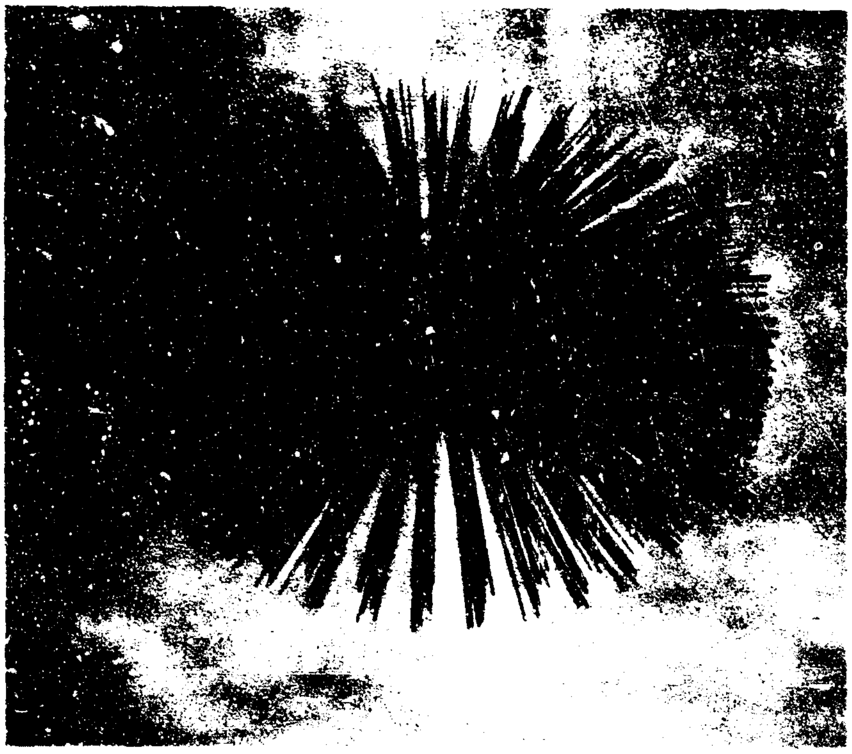

Fig. 2: Single Brush with 1 mm Wires

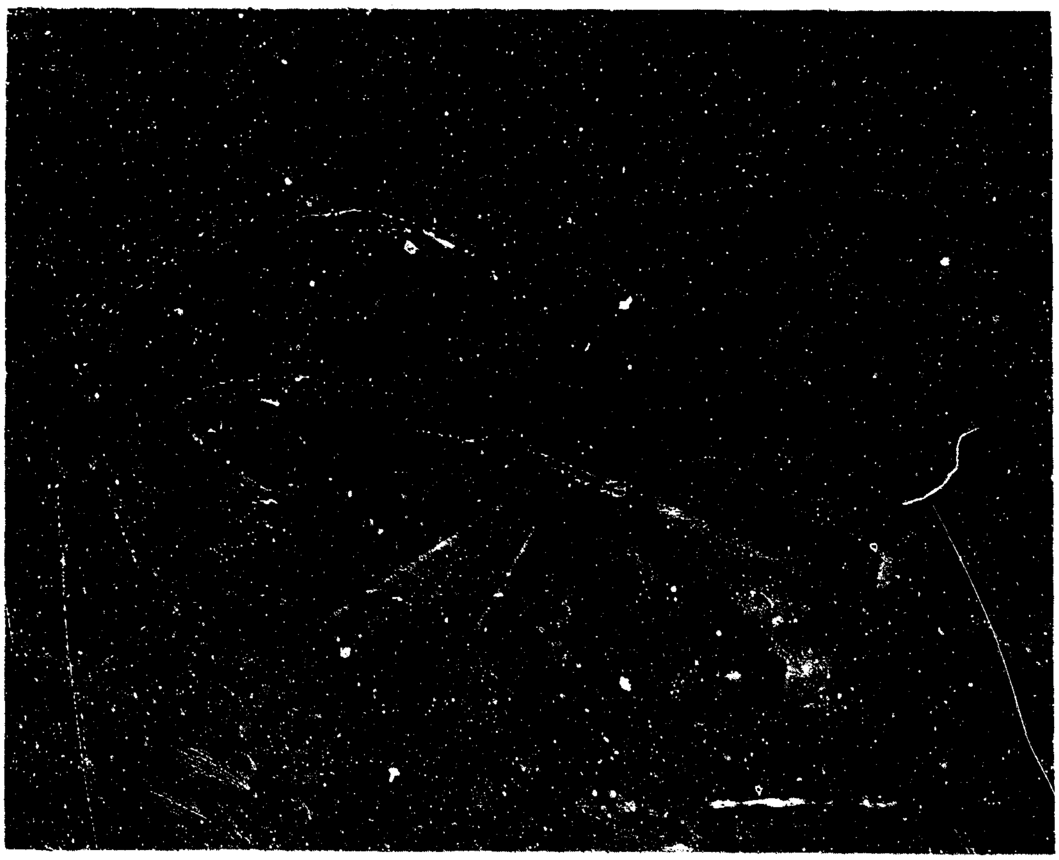

Fig. 3: Flat Blade Brush for Centrifugal Effect Tests

Fig. 4: Interior of Brush Housing

housing on the downstream side is shown in Fig. 5. A photograph of the brush separator test layout is shown in Fig. 6.

In normal operation, the separated dust was drawn off from the downstream periphery of the brush with a small fraction of the air, usually about 250 CFM. This purge air carrying the dust concentrate was discharged through a cyclone dust collector. A slide valve regulated the purge air volume. Flowrate was determined from pressure drop measurements across the cyclone.

The test dusts, usually sodium bicarbonate, were introduced at the outlet of the 25 HP fan. A Sylco dust feeder was used to entrain the dust in a 1 CFM airstream. The dust inlet upstream of the separator was modified by introducing the dust more uniformly through a horizontal manifold with nine holes, either facing up, down, or in the direction of flow near the center of the duct. A six inch wide, vertical, perforated-plate baffle was placed eight inches downstream of the horizontal dust manifold to further disperse the dust. In this manner, a more uniform dust distribution was possible in the relatively short distance between the dust inlet and the upstream sampling probe. The sampling probes were also changed. Instead of a single, horizontal-flute sampling probe across the center of the duct as originally used, two flute probes at right angles to each other and 45° off the vertical, were placed normal to the line of airflow. By improving the dust feed and sampling techniques, the variation in concentration between the upstream and downstream sampling probes with a static brush (flat-blades) was reduced to less than 1.3% in the average of three tests with a maxiumum variation of $\pm$ 5.5%. This small variation indicates representative sampling.

The filter sample flowrate was also increased to nearly 6 CFM from the original 1.3 CFM value, thereby increasing the amount of collected dust and enhancing the accuracy of the measurements. The increased flowrate was made possible by the use of a glass-fiber Type E (Gelman) filter of 47 mm diameter, instead of the plastic membrane filters used previously.

The analytical procedure for analysis of the sodium bicarbonate was also modified by using bromocresol green indicator and boiling the acid titrated solution to avoid the supersaturation by carbon dioxide which would otherwise mask the true endpoint. Precise endpoints now pinpoint bicarbonate contents precisely.

All of the above modifications reduced experimental errors to the point where running tests in triplicate, as in the previous program, is unnecessary and wasteful. Tests, instead, were run in duplicate, permitting the investigation of additional parametric factors or levels.

Fig. 5: Three Brushes Mounted on the Shaft

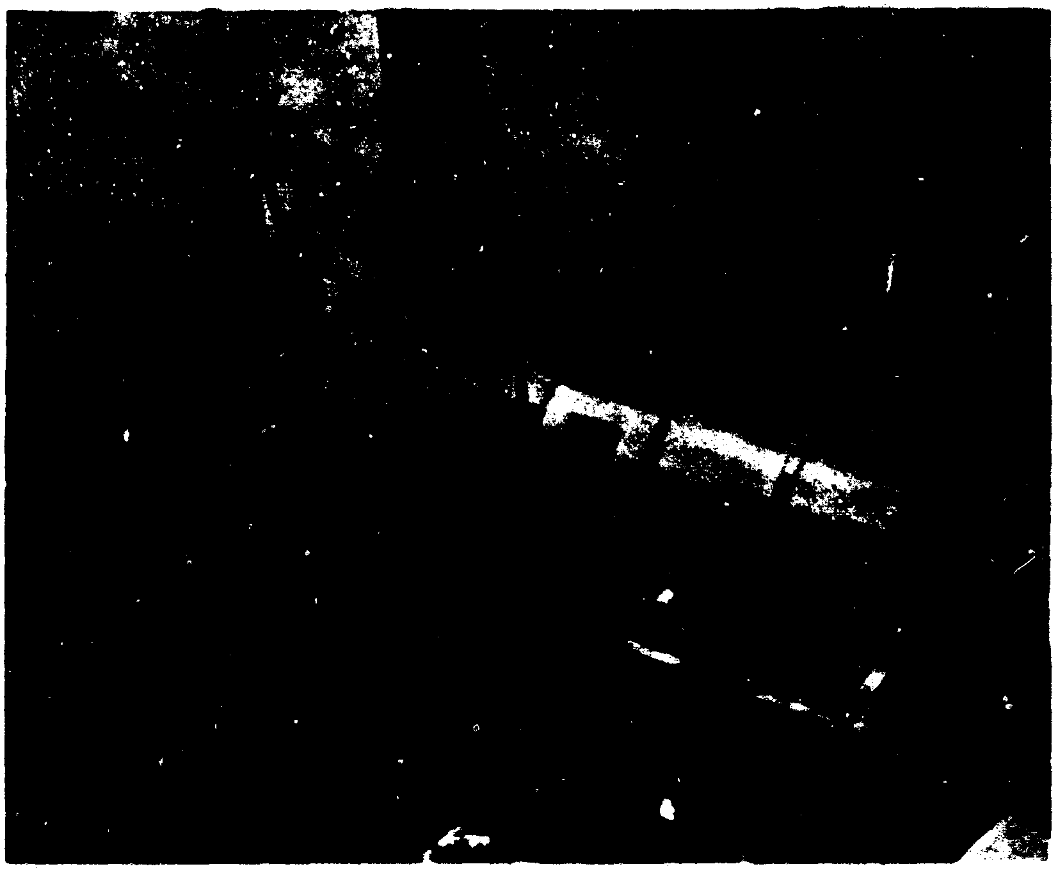

Fig 6: Brush Separator Test Layout

B. Flow Measurements

A comprehensive calibration of the brush separator and purge cyclone flowrates had been obtained previously by three independent measurements which agreed to within ± 5% (see Ref. 5). These calibrations were checked in the current investigation through the use of the orifice flow equation which confirmed the previous calculations. Therefore, the reader is referred to Ref. 5 for the detailed flow data and the description of the calibration techniques used.

The pressure drop through the brush separator is a function of the air flow. At 8000 CFM, the pressure drop is only four inches of water as shown in Fig. 7 of the previous reference.

C. Size Distribution of the Test Dusts

A fire extinguishing chemical, Ansul +50B sodium bicarbonate, was used for most of the efficiency tests. The size distribution of this material had been measured by separating into narrow-size fractions with a Bahco classifier and microscopically sizing the weighed fractions, Fig. 7. In the last series of tests, large quantities of Bahco fractionated sodium bicarbonate with median diameters of 15-, 33-, and 44 μm were prepared and used to establish separation efficiency and particle size relationships. The smallest particle size range was covered with a ball-milled anthracite coal powder with a mass median diameter of 2.7 μm, as determined by Andreason pipette sedimentation measurements.

D. Test Procedure

The details of the test procedure used for all tests utilizing the Ansul test dust are given in Appendix B. In tests utilizing coal dust, the filter analysis was gravimetric instead of volumetric.

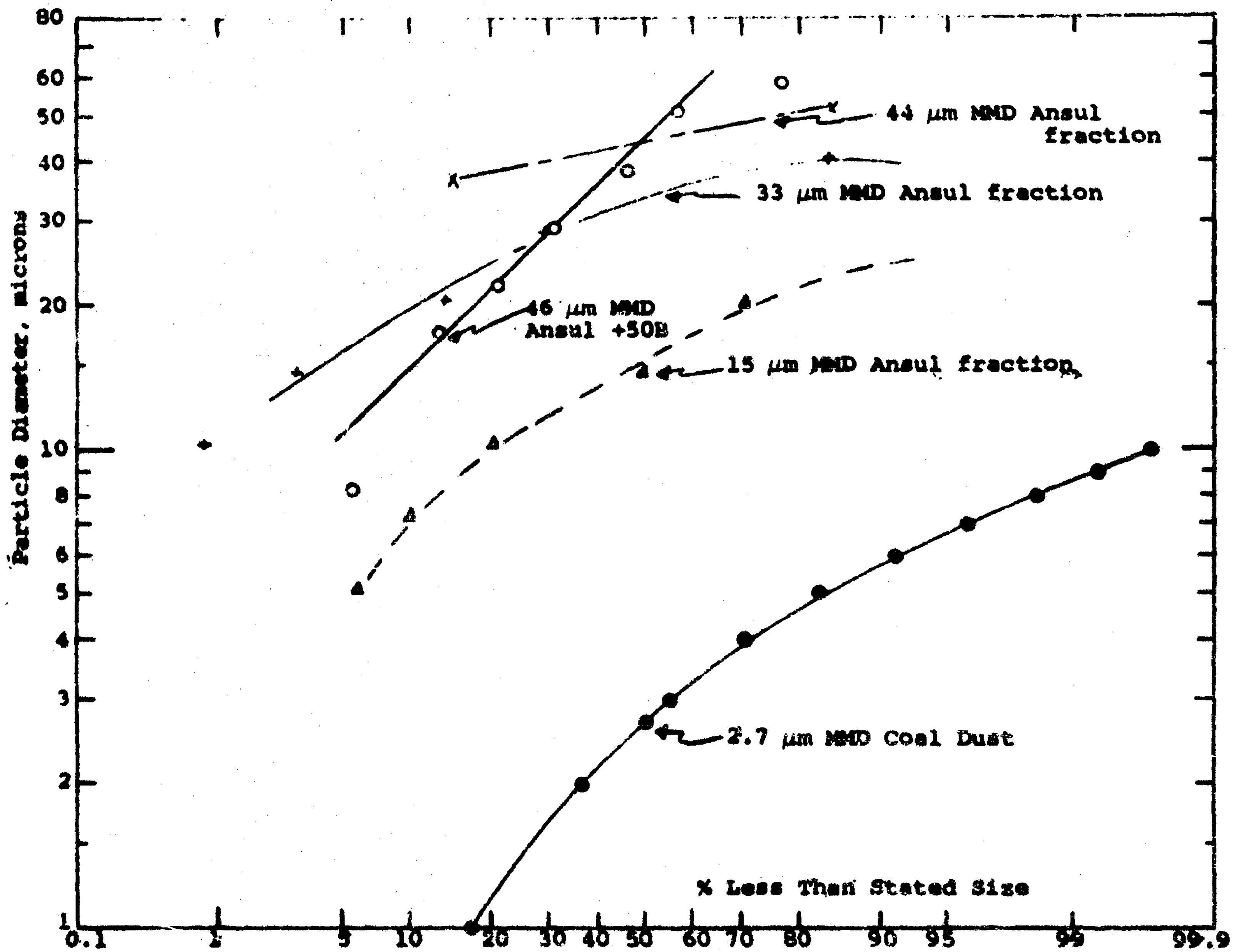

Fig. 7: Size Distribution of the Test Dusts

III. RESULTS AND DISCUSSION

A. Tabulated Data and Noncomparative Plots

The results of the brush separator efficiency tests are presented in Table 1. Twelve different brush configurations utilizing flat blades and two different wire sizes were tested at four brush speeds in the range of from 1200-to 3000 RPM as shown in Figs. 8 through 27. Generally, the separation efficiency and brush horsepower increased as the brush RPM increased. Brush horsepower was calculated from the hydraulic fluid pressure drop across the drive motor and the hydraulic fluid flowrate through the motor. Detailed comparisons are made in the following section.

B. Comparative Parametric Analysis

The parameters which were investigated are residence time (exhaust position), centrifugal effects, wire spacing, impaction area, wire diameter, and dust particle size. Most of the figures in this section are overlays of comparative figures from the preceding section (Figs. 8-27) to simplify the comparison.

1. Residence Time (Exhaust Position)

The effect of the residence time on separation efficiency was determined by varying the position of the exhaust annulus. In the near exhaust position, the exhaust annulus which separated the cleaned airstream from the particle-laden dirty airstream was located immediately after the last brush. In the far exhaust position, the inner aluminum cylinder (Part C614, Appendix A) was removed so that the two airstreams separated some 16-1/2 inches further downstream. This allowed additional time for the spinning action of the airstream to take place prior to splitting the clean and dirty airstreams.

There was no pronounced difference in separation efficiency relative to exhaust position with the flat blades at 8000 CFM over the range of 1200 to 3000 RPM, although slightly less horsepower was required with the near exhaust, Fig. 28. Separation efficiency appears to approach a maximum of about 88% in the region of 2400-3000 RPM, with brush horsepower increasing rapidly with increasing RPM.

With the 1-mm wire brushes, Figs. 29 and 30, the effect of exhaust position on separation efficiency was much more pronounced than with the flat-blades. Note that the total projected area of the 1-mm wires in these tests is the same as the projected area of the flat-blades. At 8000 CFM, Fig. 29, the near exhaust resulted in separation efficiencies approaching 95% at 3000 RPM, whereas with the far exhaust, the efficiency peaked at 85% at 2400 RPM and fell off to below 70% at 3000 RPM. Similarly, at a constant brush RPM of 2400 and varying inlet air CFM, Fig. 30, the near exhaust

Table 1

BRUSH SEPARATOR EFFICIENCY TESTS WITH ANSUL $NaHCO_3$

Test No.	Brushes	Wire Size	Wires/Row	Rows/Brush	Brush, RPM	Exhaust Annulus	Inlet Air, CFM	Purge Air, CFM	Dust Concentration mg/ft^3	Brush Horsepower	Efficiency Percent	Average Efficiency Percent	Test Dust
6	4	47.6 BLADE FLAT	12	1	0	Near	8000	230	4.77	0	+3.3		
7	4		12	1	0	Near	8000	230	6.76	0	-1.1	0.4 ± 4.8 (4) (Blank)	
10	4		12	1	0	Near	8000	230	6.40	0	[illegible]		
11b	4		12	1	0	Near	8000	215	7.34	0	+3.7		
8	4		12	1	1800	Near	8000	240	6.08	3.21	83.7	81.1	A
9	4		12	1	1800	Near	8000	240	6.25	3.14	78.5		A
12	4		12	1	2400	Near	8000	245	8.67	6.06	89.3	88.0	A
13	4		12	1	2400	Near	8000	250	6.29	5.40	86.7		A
14	4		12	1	3000	Near	8000	270	9.24	7.90	82.3	85.5	A
15	4		12	1	3000	Near	8000	270	8.77	7.90	88.8		A
16	4		12	1	1200	Near	8000	240	8.83	2.00	62.2	64.1	A
17	4		12	1	1200	Near	8000	240	7.75	1.59	66.0		A
18	4		12	1	1200	Near	4650	240	8.00	1.40	73.8	72.5	A
19	4		12	1	1200	Near	4650	240	8.18	1.36	71.2		A
20	4		12	1	1200	Near	3280	240	8.63	1.06	80.8	80.4	A
21	4		12	1	1200	Near	3280	245	8.86	1.06	80.1		A
22	4		12	1	1800	Far	8000	210	8.82	4.43	81.8	81.0	A
23	4		12	1	1800	Far	8000	210	7.97	4.14	80.3		A
24	4		12	1	2400	Far	8000	220	8.05	6.26	87.1	86.3	A
25	4		12	1	2400	Far	8000	220	7.40	5.87	85.6		A
26	4		12	1	3000	Far	8000	247	8.50	9.32	86.5	86.8	A
27	4		12	1	3000	Far	8000	230	8.40	8.72	87.0		A
28	4		12	1	1200	Far	8000	195	8.8[illegible]	1.58	73.0	70.0	A
29	4		12	1	1200	Far	8000	190	8.45	2.11	67.0		A
30	4		12	1	1200	Far	4650	230	8.45	1.40	77.1	76.3	A
31	4		12	1	1200	Far	4650	230	9.20	1.29	75.5		A
32	4		12	1	1200	Far	3280	240	8.06	1.08	78.0	78.7	A
33	4		12	1	1200	Far	3280	240	8.17	1.12	79.4		A

Table 1 (Cont'd)

BRUSH SEPARATOR EFFICIENCY TESTS WITH ANSUL $NaHCO_3$

Test No.	Brushes	Wire Size	Wires/Row	Rows/Brush	Brush, RPM	Exhaust Annulus	Inlet Air, CFM	Purge Air, CFM	Dust Concentration mg/ft^3	Brush Horsepower	Efficiency Percent	Average Efficiency Percent	Test Dust
34	4	1 mm	48	12	1800	Far	8000	190	9.20	2.57	70.3	73.1	A
35	4	1 mm	48	12	1800	Far	8000	190	8.58	2.50	76.0		A
36	4	1 mm	48	12	2400	Far	8000	210	6.72	4.27	85.0	85.2	A
37	4	1 mm	48	12	2400	Far	8000	210	7.80	4.38	85.4		A
38	4	1 mm	48	12	3000	Far	8000	240	8.55	6.69	66.3	68.4	A
39	4	1 mm	48	12	3000	Far	8000	245	8.12	6.81	70.5		A
40	4	1 mm	48	12	1200	Far	8000	180	8.38	0.93	34.1	35.6	A
41	4	1 mm	48	12	1200	Far	8000	190	7.90	0.93	37.0		A
42	4	1 mm	48	12	2400	Far	4650	220	8.42	4.27	90.8	88.2	A
43	4	1 mm	48	12	2400	Far	4650	220	8.27	4.27	85.6		A
44	4	1 mm	48	12	2400	Far	3280	230	8.83	4.27	75.6	74.8	A
45	4	1 mm	48	12	2400	Far	3280	230	9.03	4.27	74.0		A
46	4	1 mm	48	12	1800	Near	8000	250	8.45	2.36	69.1	71.9	A
47	4	1 mm	48	12	1800	Near	8000	250	8.61	2.36	74.7		A
48	4	1 mm	48	12	2400	Near	8000	250	8.40	4.27	37.7	88.4	A
49	4	1 mm	48	12	2400	Near	8000	250	8.67	4.27	89.2		A
50	4	1 mm	48	12	3000	Near	8000	280	9.18	6.70	94.8	95.1	A
51	4	1 mm	48	12	3000	Near	8000	280	8.92	6.70	95.4		A
52	4	1 mm	48	12	1200	Near	8000	250	8.54	0.93	47.7	45.5	A
53	4	1 mm	48	12	1200	Near	8000	250	8.50	0.93	43.3		A
54	4	1 mm	48	12	2400	Near	4650	245	8.22	4.07	90.9	90.3	A
55	4	1 mm	48	12	2400	Near	4650	250	8.80	4.17	89.8		A
56	4	1 mm	48	12	2400	Near	3280	250	9.49	4.17	96.1	95.0	A
57	4	1 mm	48	12	2400	Near	3280	250	9.36	4.17	93.9		A
58	2	1 mm	48	12	3000	Near	8000	270	8.87	5.50	87.8	89.2	A
59	2	1 mm	48	12	3000	Near	8000	270	8.93	5.50	90.7		A
60	2	1 mm	48	12	2400	Near	8000	270	8.82	3.70	75.5	72.8	A
61	2	1 mm	48	12	2400	Near	8000	270	8.52	3.60	70.1		A
62	2	1 mm	48	12	1800	Near	8000	265	8.45	2.07	62.2		A
63	2	1 mm	48	12	1800	Near	8000	260	8.81	2.07	61.3	61.7	A

Table 1 (Cont'd)

BRUSH SEPARATOR EFFICIENCY TESTS WITH ANSUL $NaHCO_3$

Test No.	Brushes	Wire Size	Wires/ Row	Rows/ Brush	Brush, RPM	Exhaust Annulus	Inlet Air, CFM	Purge Air, CFM	Dust Concen- tration mg/ft3	Brush Horse- power	Effi- ciency Percent	Average Effi- ciency Percent	Test Dust
64	2	1 mm	48	12	1200	Near	8000	260	8.53	0.89	35.3	33.9	A
65	2	1 mm	48	12	1200	Near	8000	255	8.57	0.89	32.5		A
66	2	1 mm	48	12	2400	Near	4650	270	8.36	3.41	83.8	83.5	A
67	2	1 mm	48	12	2400	Near	4650	265	8.47	3.41	83.3		A
68	2	1 mm	48	12	2400	Near	3280	250	8.58	3.03	87.2	86.8	A
69	2	1 mm	48	12	2400	Near	3280	250	8.57	3.03	86.5		A
70	4	1 mm	24	12	3000	Near	8000	255	8.57	6.22	89.6	89.4	A
71	4	1 mm	24	12	3000	Near	8000	255	8.73	6.22	89.3		A
72	4	1 mm	24	12	2400	Near	8000	250	8.53	3.79	80.2	80.3	A
73	4	1 mm	24	12	2400	Near	8000	250	8.45	3.79	80.5		A
74	4	1 mm	24	12	1800	Near	8000	240	8.78	2.15	59.1	59.7	A
75	4	1 mm	24	12	1800	Near	8000	240	8.76	2.15	60.3		A
76	4	1 mm	24	12	1200	Near	8000	250	8.63	0.84	25.8	25.3	A
77	4	1 mm	24	12	1200	Near	8000	250	8.65	0.84	24.9		A
78	4	1 mm	24	12	2400	Near	4650	245	8.36	3.41	86.8	86.3	A
79	4	1 mm	24	12	2400	Near	4650	245	8.47	3.41	85.9		A
80	4	1 mm	24	12	2400	Near	3280	245	9.17	3.22	89.5	88.4	A
81	4	1 mm	24	12	2400	Near	3280	250	9.05	3.22	87.3		A
82	4	2 mm	48	12	3000	Near	8000	270	8.31	7.05	94.9	94.0	A
83	4	2 mm	48	12	3000	Near	8000	270	8.82	7.05	93.1		A
84	4	2 mm	48	12	2400	Near	8000	270	9.14	4.65	92.3	92.2	A
85	4	2 mm	48	12	2400	Near	8000	270	8.83	4.73	92.2		A
86	4	2 mm	48	12	1800	Near	8000	260	8.47	2.86	86.7	86.5	A
87	4	2 mm	48	12	1800	Near	8000	260	8.45	2.86	86.3		A
88	4	2 mm	48	12	1200	Near	8000	260	8.75	1.21	64.7	62.7	A
89	4	2 mm	48	12	1200	Near	8000	260	8.49	1.21	60.7		A
90	4	2 mm	48	12	2400	Near	4650	270	9.43	4.54	94.9	94.4	A
91	4	2 mm	48	12	2400	Near	4650	270	9.15	4.54	93.9		A
92	4	2 mm	48	12	2400	Near	3280	250	9.20	4.17	93.5		A
93	4	2 mm	48	12	2400	Near	3280	255	8.91	4.17	92.9	93.2	A

Table 1 (Cont'd)

BRUSH SEPARATOR EFFICIENCY TESTS WITH ANSUL $NaHCO_3$

Test No.	Brushes	Wire Size	Wires/ Row	Rows/ Brush	Brush, RPM	Exhaust Annulus	Inlet Air, CFM	Purge Air, CFM	Dust Concentration mg/ft^3	Brush Horsepower	Efficiency Percent	Average Efficiency Percent	Test Dust
94	2	2 mm	48	12	3000	Near	8000	280	8.04	6.22	87.2	87.0	A
95	2	2 mm	48	12	3000	Near	8000	280	8.44	6.22	86.9		A
96	2	2 mm	48	12	2400	Near	8000	280	8.65	3.79	83.8	83.2	A
97	2	2 mm	48	12	2400	Near	8000	280	8.46	3.79	82.7		A
98	2	2 mm	48	12	1800	Near	8000	275	8.75	2.43	62.5	61.2	A
99	2	2 mm	46	12	1800	Near	8000	275	8.65	2.43	60.0		A
100	2	2 mm	48	12	1200	Near	8000	265	8.55	1.07	48.9	45.7	A
101	2	2 mm	48	12	1200	Near	8000	265	8.67	1.07	42.6		A
102	2	2 mm	48	12	2400	Near	4650	265	8.36	3.79	82.9	82.9	A
103	2	2 mm	48	12	2400	Near	4650	270	8.56	3.79	82.9		A
104	2	2 mm	48	12	2400	Near	3280	245	8.99	3.41	90.6	89.9	A
105	2	2 mm	48	12	2400	Near	3280	245	8.77	3.41	89.2		A
106	2	2 mm	24	12	3000	Near	8000	265	8.55	6.10	80.0	79.5	A
107	2	2 mm	24	12	3000	Near	8000	265	8.54	6.10	79.0		A
108	2	2 mm	24	12	2400	Near	8000	265	9.23	3.50	59.1	60.6	A
109	2	2 mm	24	12	2400	Near	8000	265	8.83	3.50	62.2		A
110	2	2 mm	24	12	1800	Near	8000	265	9.03	2.14	52.9	51.7	A
111	2	2 mm	24	12	1800	Near	8000	265	8.71	2.14	50.5		A
112	2	2 mm	24	12	1200	Near	8000	255	8.90	0.93	35.4	35.8	A
113	2	2 mm	24	12	1200	Near	8000	255	8.98	0.93	36.2		A
114	2	2 mm	24	12	2400	Near	5860	255	8.92	3.41	83.7	83.0	A
115	2	2 mm	24	12	2400	Near	860	255	8.88	3.41	82.3		A
116	2	2 mm	24	12	2400	Near	3600	250	9.48	3.03	83.7	83.0	A
117	2	2 mm	24	12	2400	Near	3500	250	9.27	3.03	82.2		A
118	4	2 mm	12	12	3000	Near	8000	260	9.20	6.21	89.7	89.4	A
119	4	2 mm	12	12	3000	Near	8000	260	9.66	6.21	89.2		A
120	4	2 mm	12	12	2400	Near	8000	250	9.38	4.07	78.7	79.1	A
121	4	2 mm	12	12	2400	Near	3000	255	9.12	4.07	79.5		A
122	4	2 mm	12	12	1800	Near	8000	255	8.32	2.29	50.4	53.9	A
123	4	2 mm	12	12	1800	Near	8000	255	9.21	2.29	57.4		A

Table 1 (Cont'd)

BRUSH SEPARATOR EFFICIENCY TESTS WITH ANSUL $NaHCO_3$

Test No.	Brushes	Wire Size	Wires/ Row	Rows/ Brush	Brush, RPM	Exhaust Annulus	Inlet Air, CFM	Purge Air, CFM	Dust Concentration mg/ft^3	Brush Horsepower	Efficiency Percent	Average Efficiency Percent	Test Dust
124	4	2 mm	12	12	1200	Near	8000	255	8.53	0.93	27.1	26.6	A
125	4	2 mm	12	12	1200	Near	8000	250	8.75	0.93	26.1		A
126	4	2 mm	12	12	2400	Near	5860	245	8.66	3.98	82.3	82.2	A
127	4	2 mm	12	12	2400	Near	5960	250	8.52	3.98	82.2		A
128	4	2 mm	12	12	2400	Near	3600	250	8.95	3.60	85.7	84.9	A
129	4	2 mm	12	12	2400	Near	3600	250	8.69	3.60	84.1		A
130	4	2 mm	48	12	3000	Near	8000	305	7.79	6.93	100.1	99.8	B
131	4	2 mm	48	12	3000	Near	8000	305	7.54	6.93	99.6		B
132	4	2 mm	48	12	3000	Near	8000	305	9.99	6.93	99.2	99.7	C
133	4	2 mm	48	12	3000	Near	8000	305	9.47	6.93	102.2		C
134	4	2 mm	48	12	3000	Near	8000	305	8.38	6.93	98.8	98.3	D
135	4	2 mm	48	12	3000	Near	8000	310	8.64	6.93	97.8		D
142	4	2 mm	48	12	3000	Near	8000	310	0.70	6.93	71.8		E
143	4	2 mm	48	12	3000	Near	8000	315	1.04	6.93	60.1	66.5	E
144	4	2 mm	48	12	3000	Near	8000	315	1.19	6.93	67.7		E

A = Ansul +50B - $NaHCO_3$, 46 μMMD

B = Bahco #14 undersize (Ansul +50B), 15.0 μMMD fraction

C = Bahco # 8 undersize (Ansul +50B), 33.2 μMMD fraction

D = Bahco # 0 oversize (Ansul +50B), 44.3 μMMD fraction

E = Ball-milled anthracite coal, 2.7 μMMD

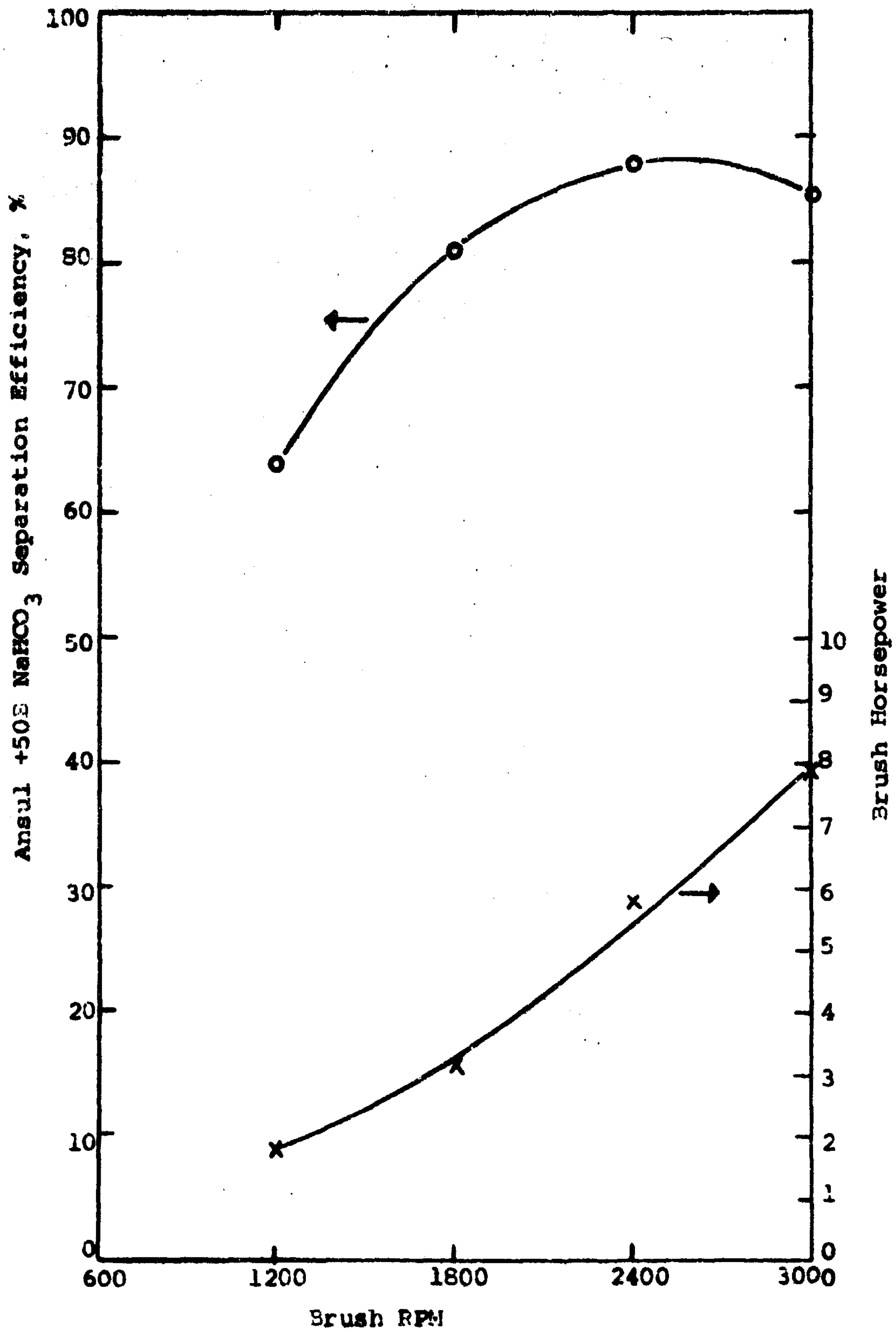

Fig. 8: Brush RPM vs Efficiency and Horsepower at 8000 CFM with Flat Blades and Near Exhaust

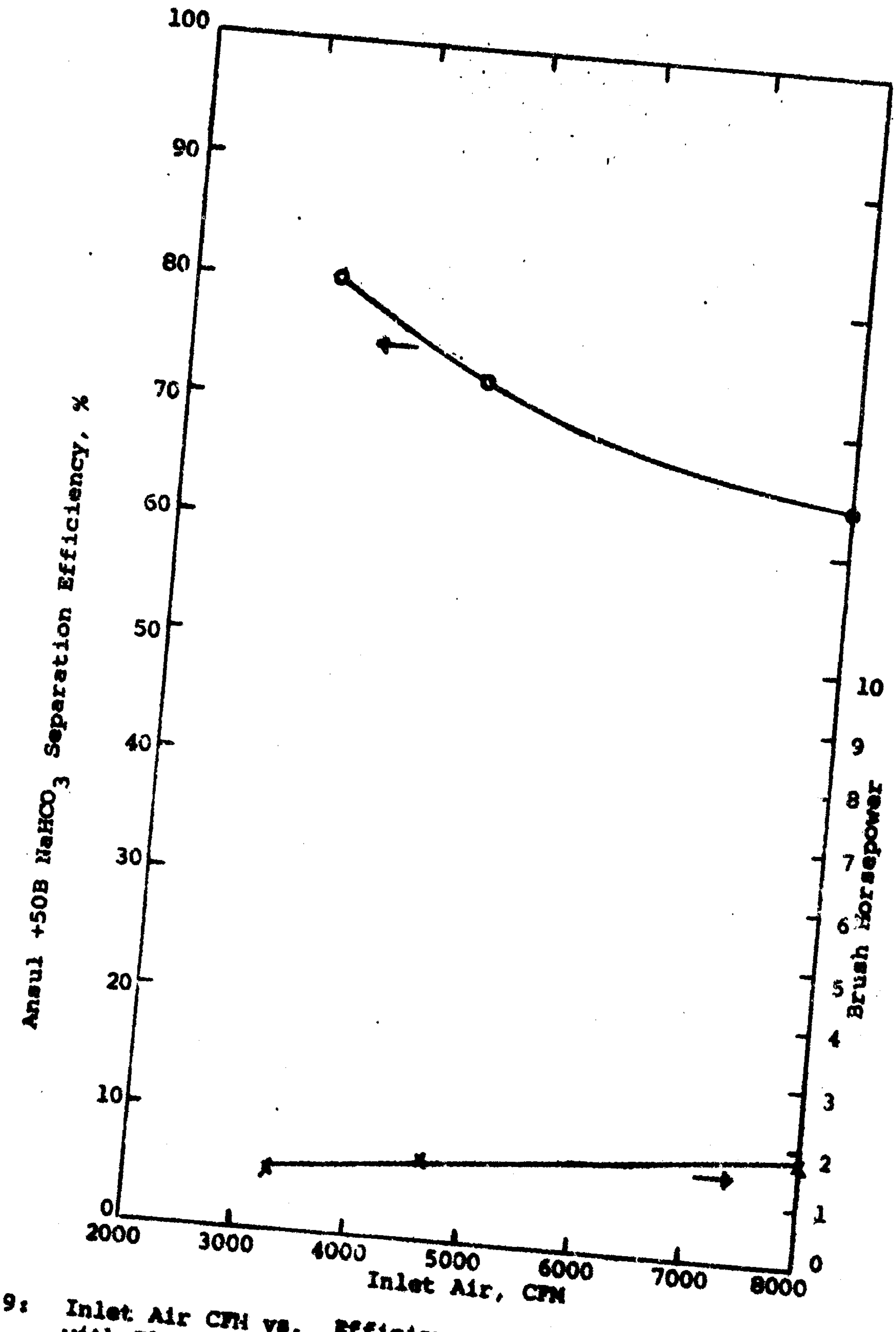

Fig. 9: Inlet Air CFM vs. Efficiency and Horsepower at 1200 RPM with Flat Blades and Near Exhaust

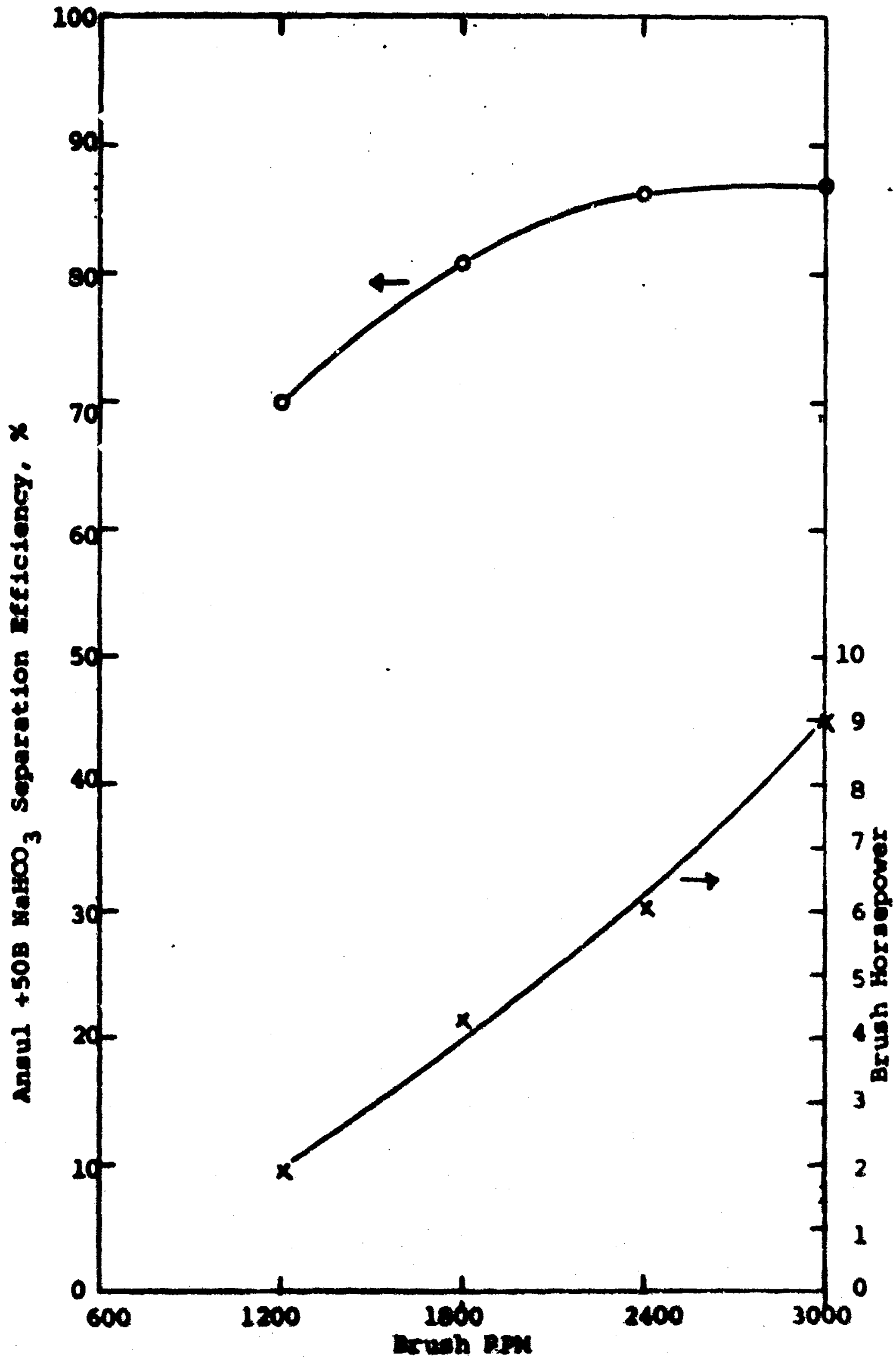

Fig. 10: Brush RPM vs Efficiency and Horsepower at 8000 CFM with Flat Blades and Far Exhaust

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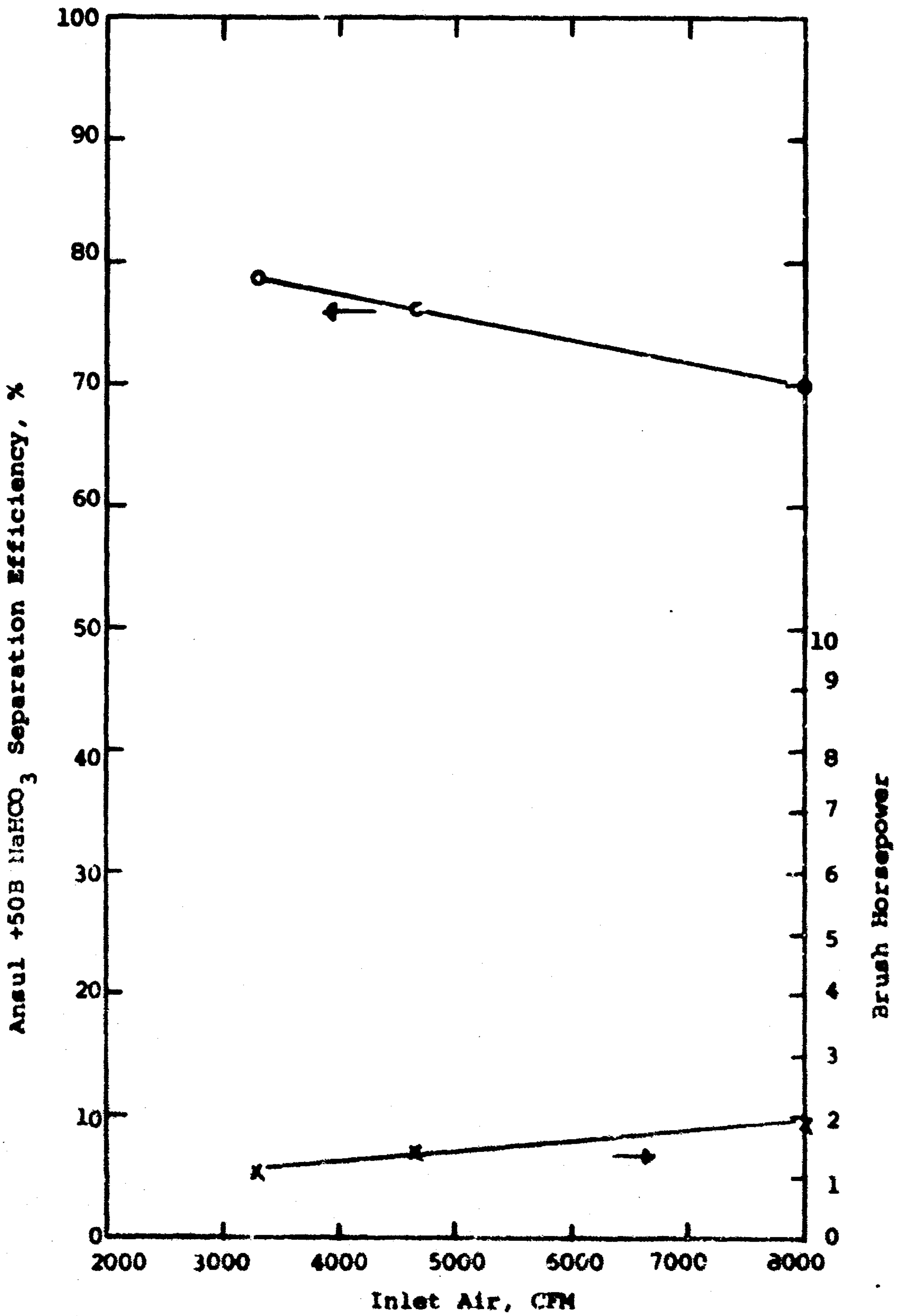

Fig.11: Inlet Air CFM vs Efficiency and Horsepower at 1200 RPM with Flat Blades and Far Exhaust

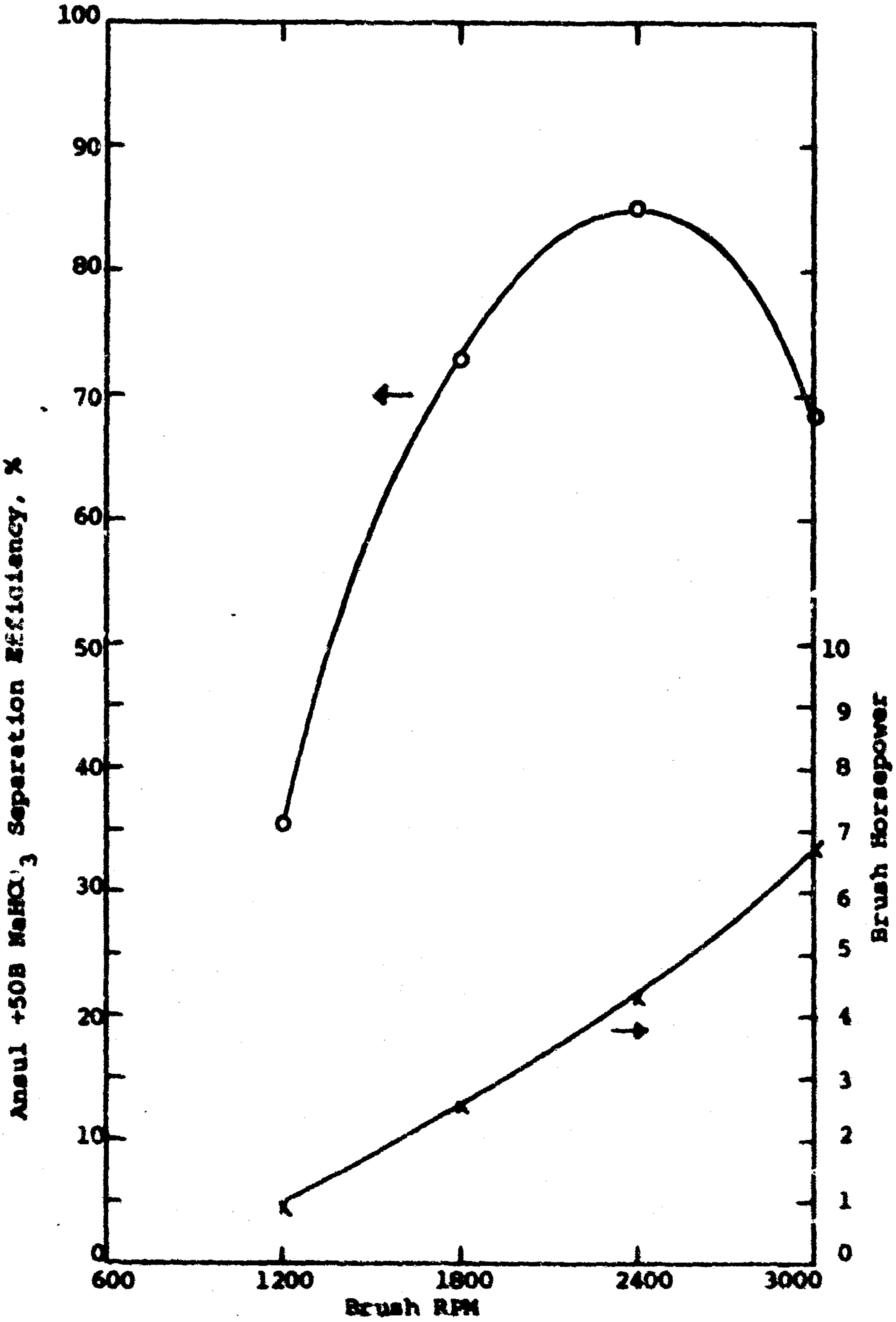

Fig. 12: Brush RPM vs Efficiency and Horsepower at 8000 CFM with Far Exhaust and 1 mm wires (4 brushes, 48 wires/row, 12 rows/brush

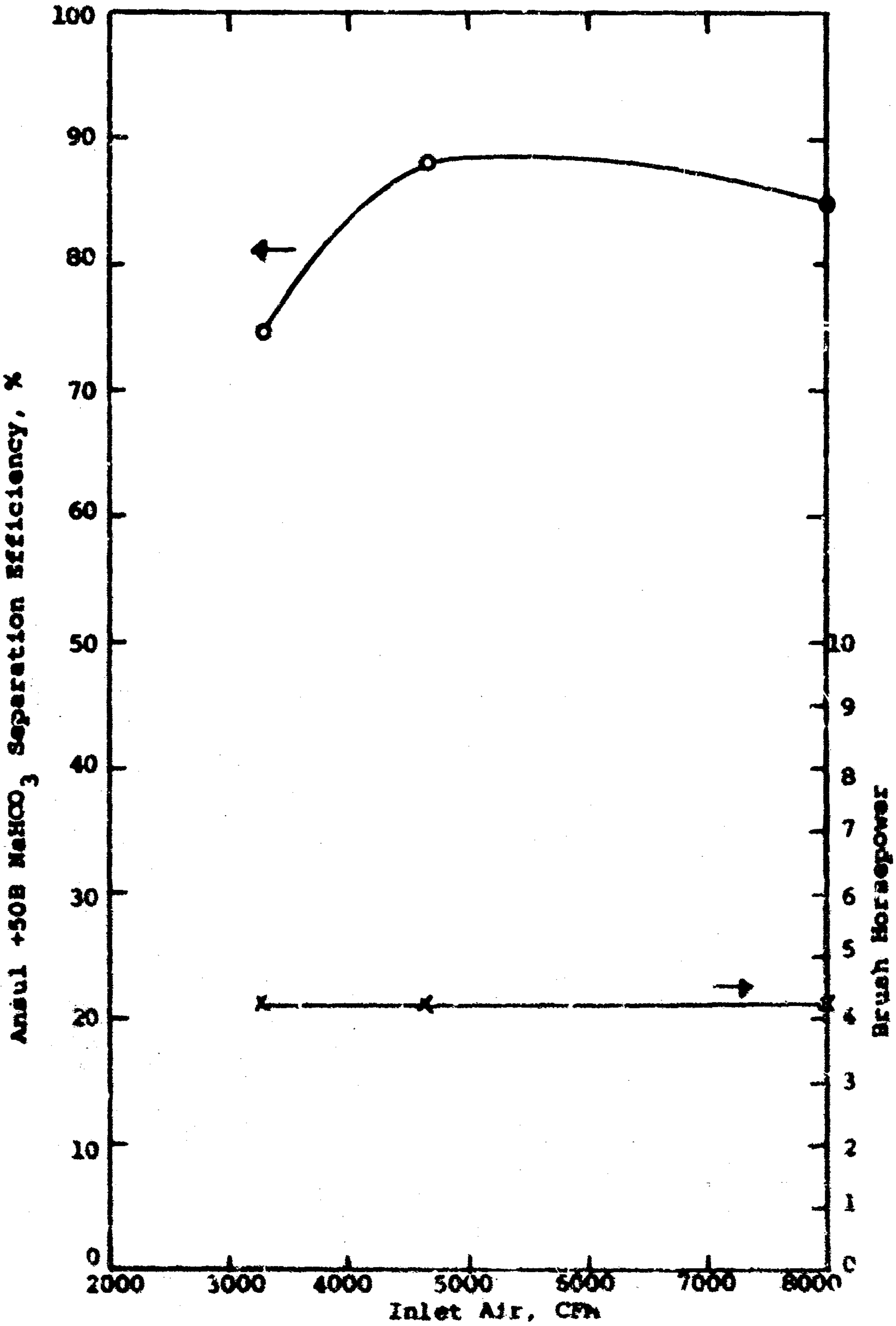

Fig. 13: Inlet Air CFM vs Efficiency and Horsepower at 2400 RPM with Far Exhaust and 1 mm wires (4 brushes, 48 wires/row, 12 rows/brush)

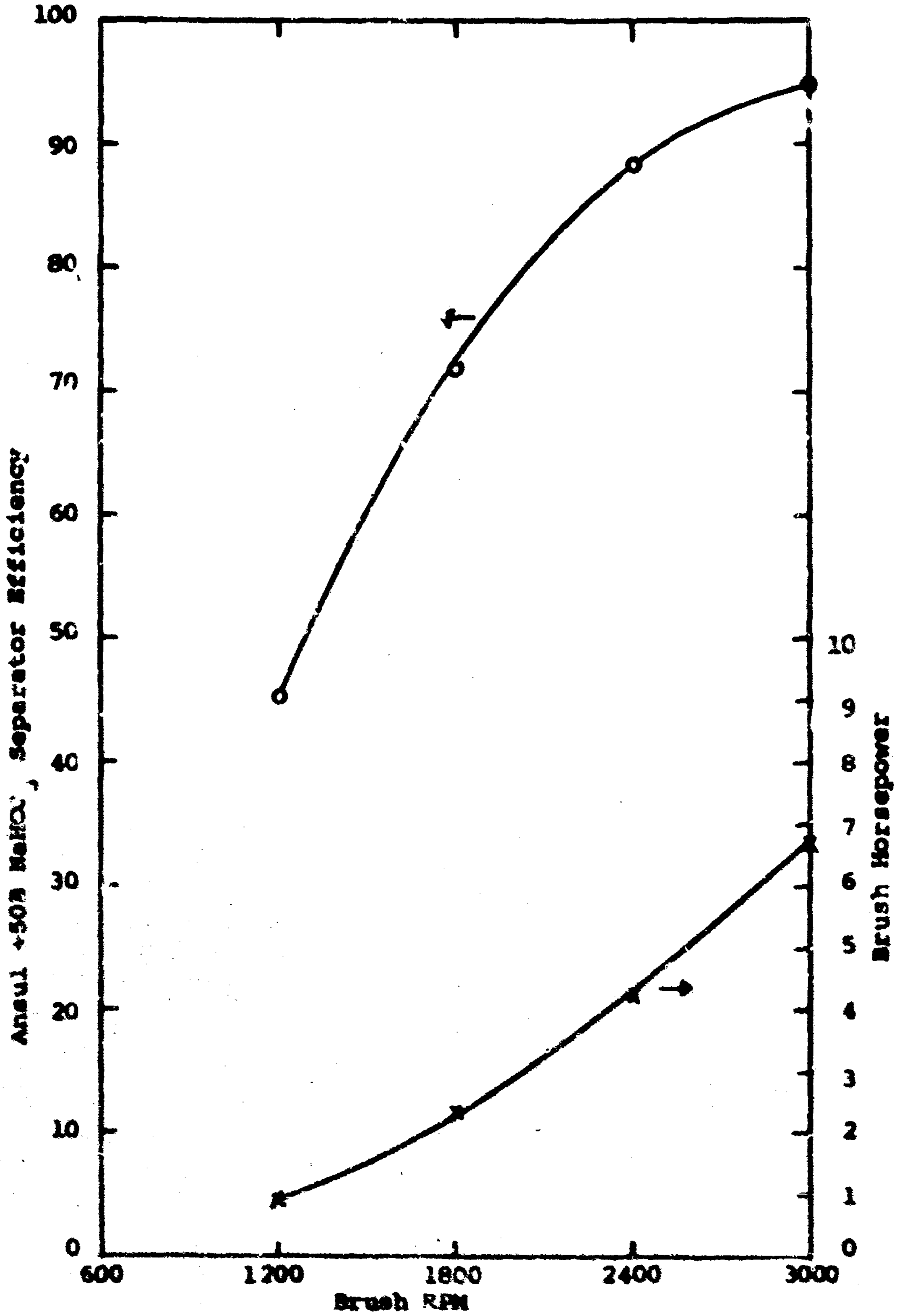

Fig. 14: Brush RPM vs Efficiency and Horsepower at 8000 CFM with Near Exhaust and 1 mm Wires (4 brushes, 48 wires/row, 12 rows/brush)

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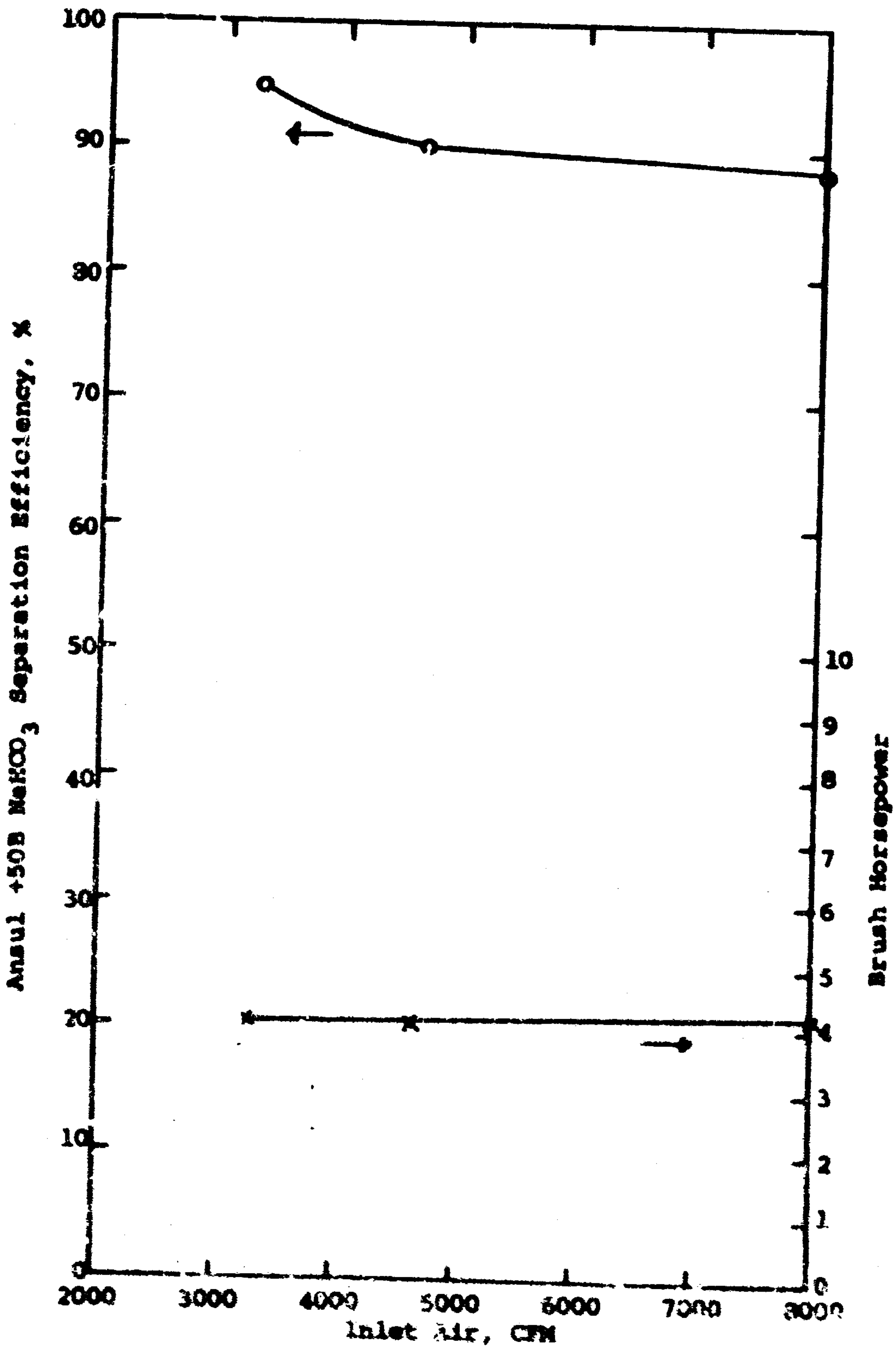

Fig. 15: Inlet Air CFM vs Efficiency and Horsepower at 2400 RPM with Near Exhaust and 1 mm Wires (4 brushes, 48 wires/row, 12 rows/brush)

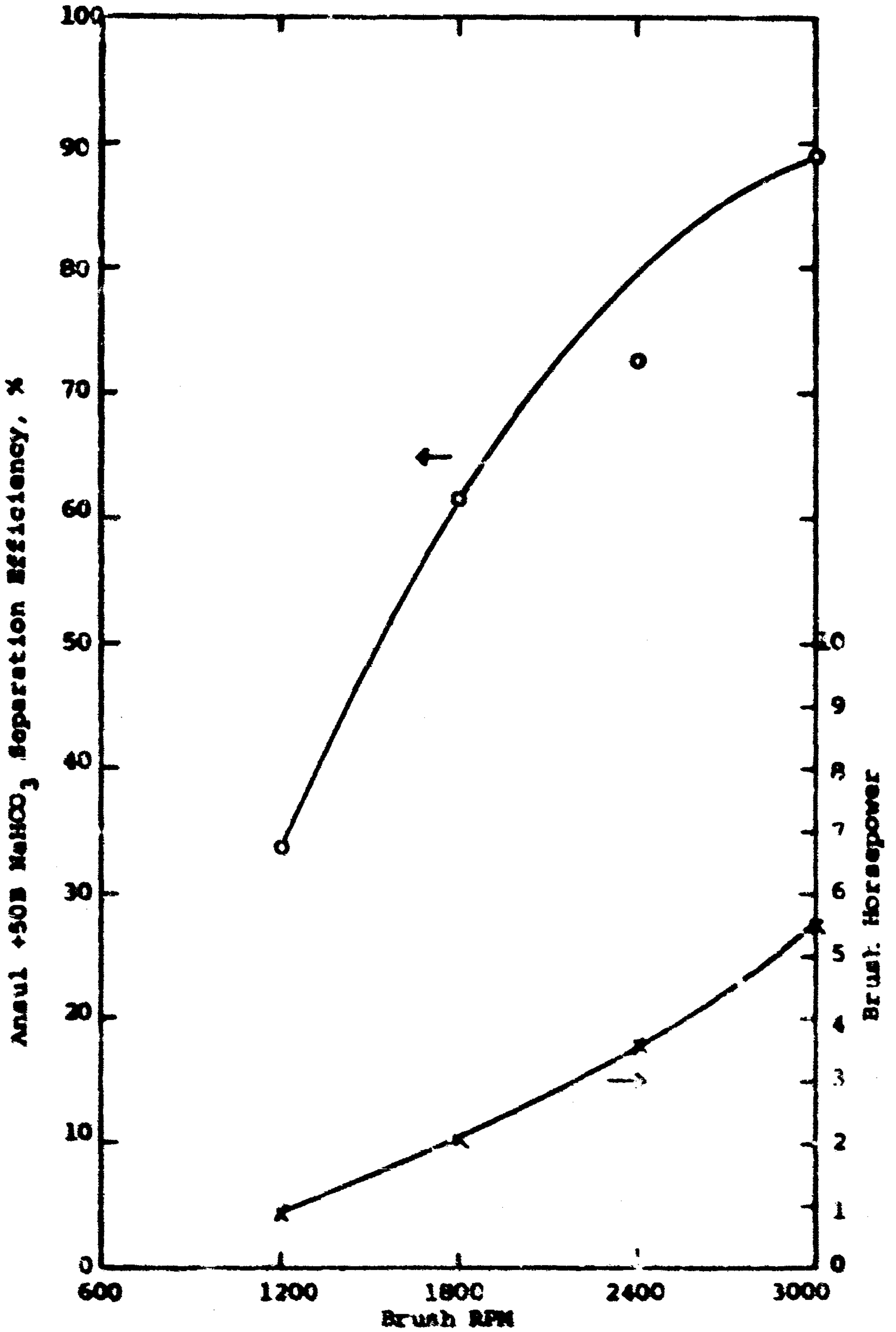

Fig. 16: Brush RPM vs Efficiency and Horsepower at 8000 CFM with Near Exhaust and 1 mm Wires (2 brushes, 48 wires/row, 12 rows/brush)

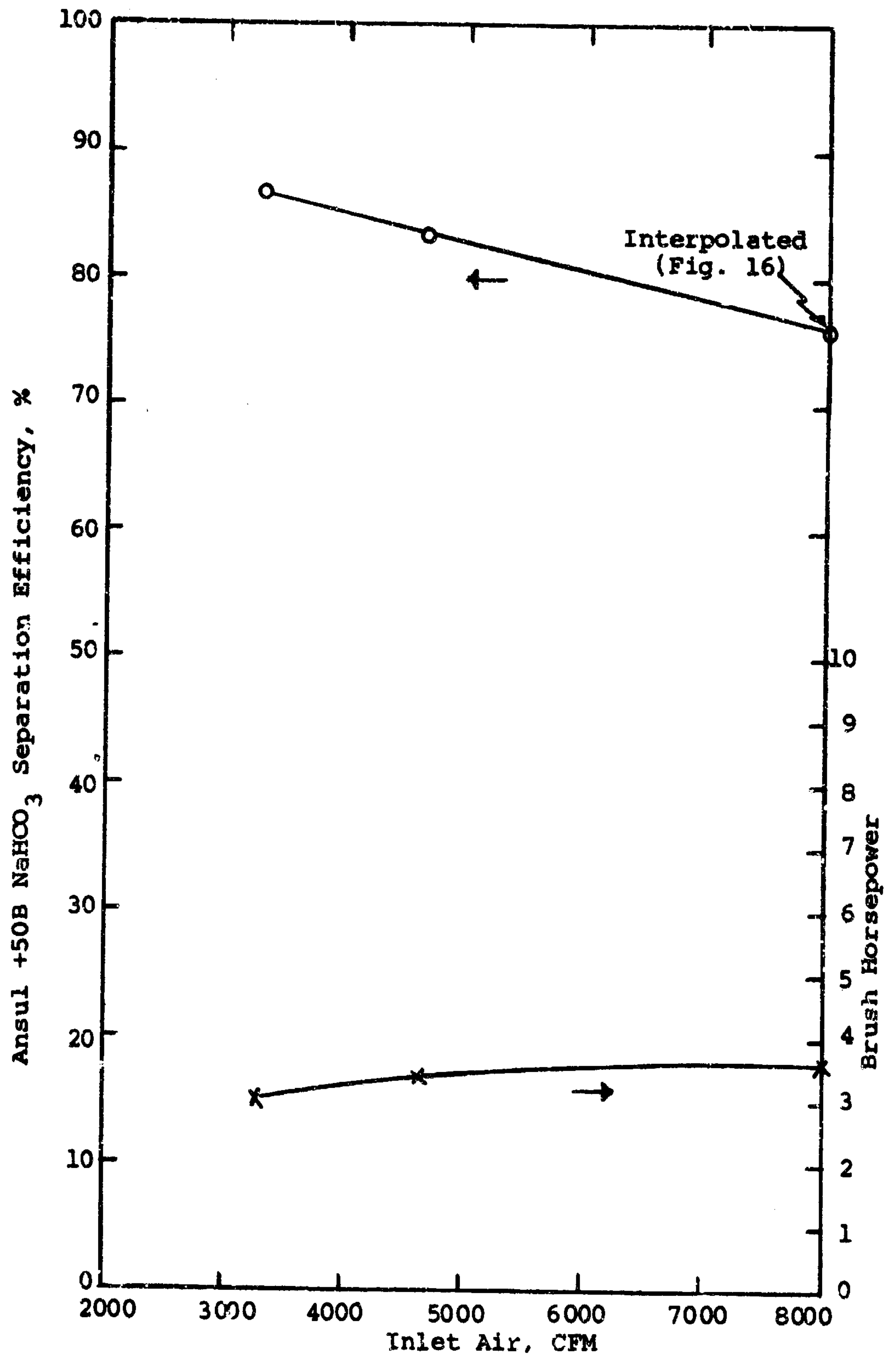

Fig. 17: Inlet Air CFM vs Efficiency and Horsepower at 2400 RPM with Near Exhaust and 1 mm Wires (2 brushes, 48 wires/row, 12 rows/brush)

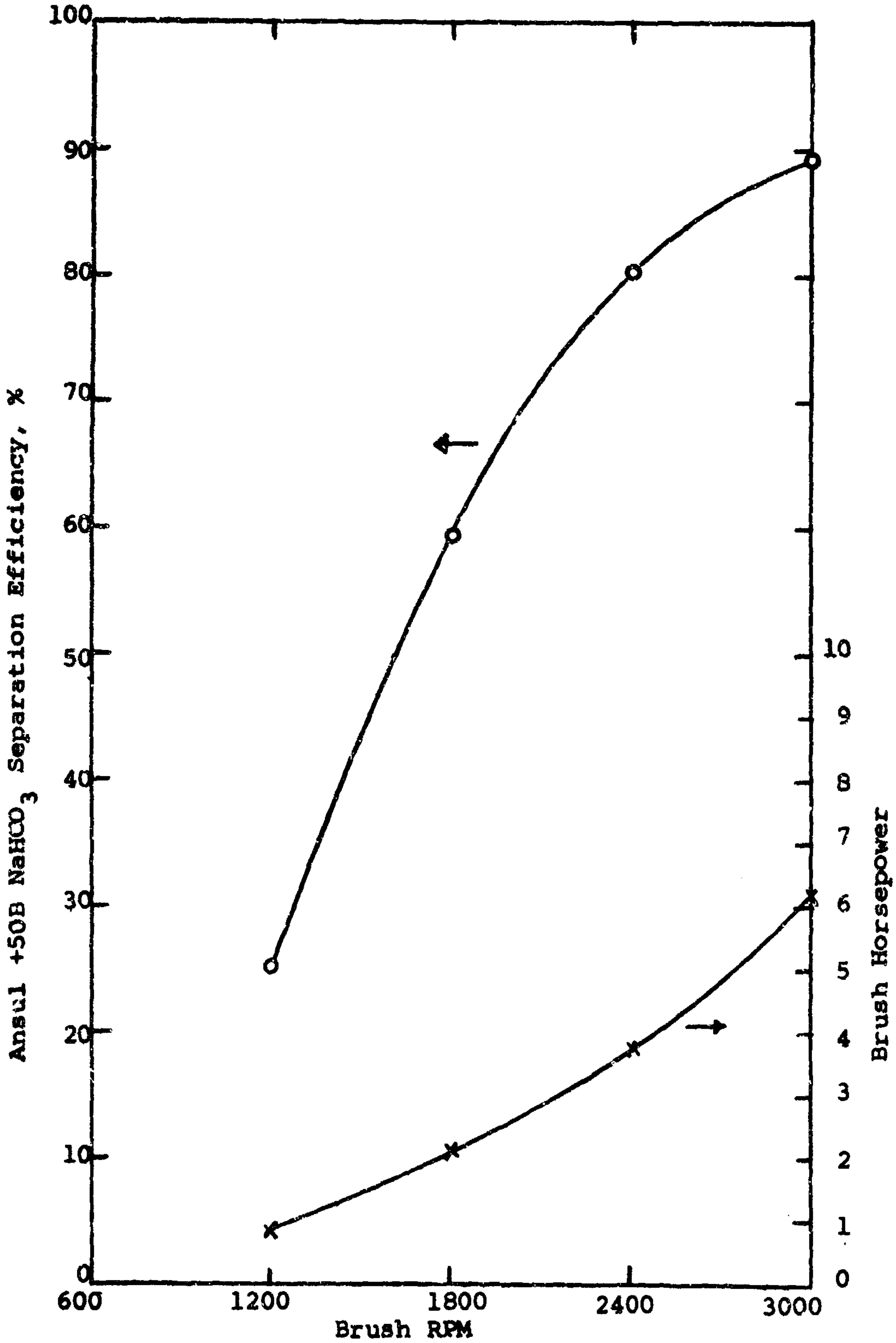

Fig. 18: Brush RPM vs Efficiency and Horsepower at 8000 CFM with Near Exhaust and 1 mm Wires (4 brushes, 24 wires/row, 12 rows/brush)

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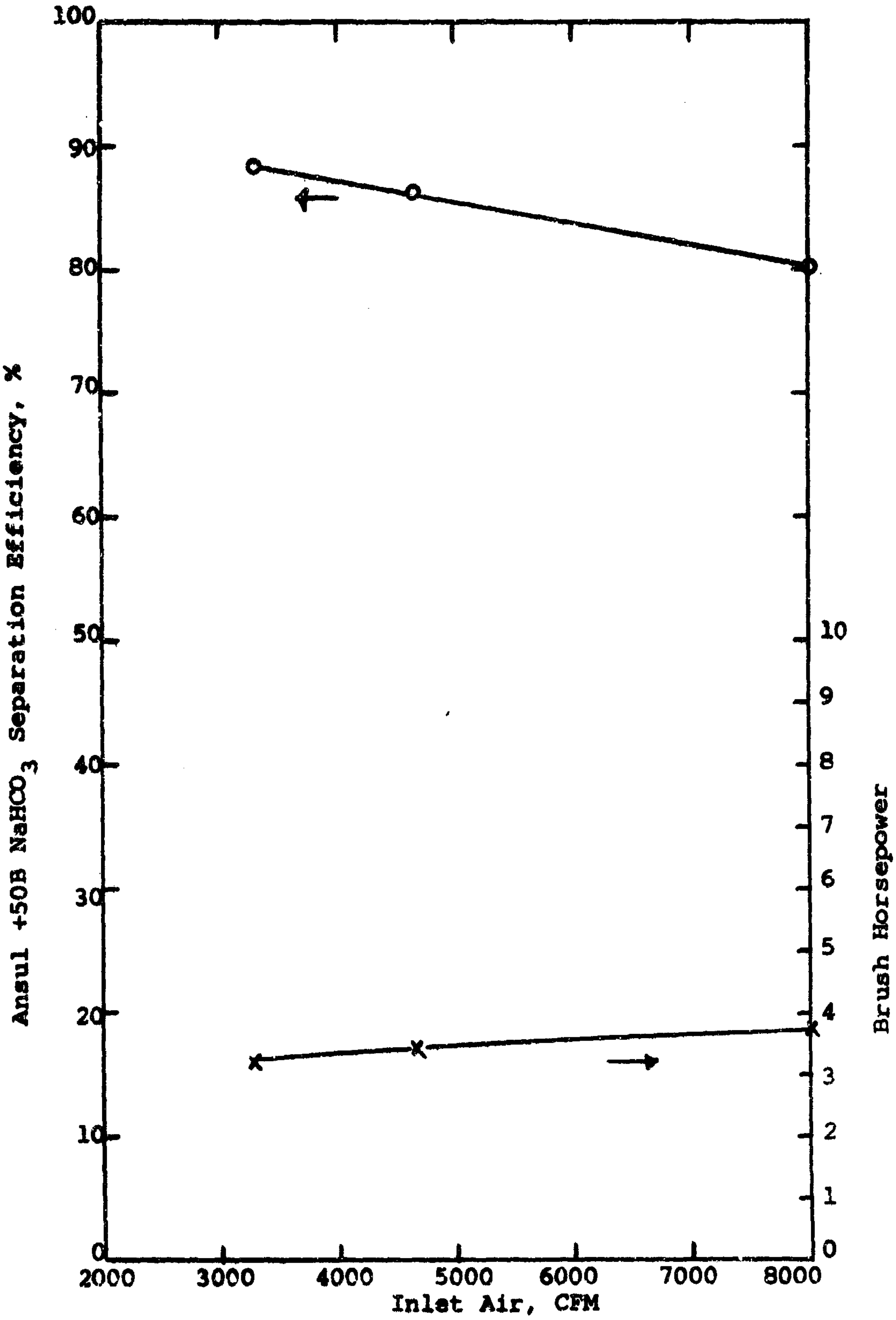

Fig. 19: Inlet Air CFM vs Efficiency and Horsepower at 2400 RPM with Near Exhaust and 1 mm Wires (4 brushes, 24 wires/row, 12 rows/brush)

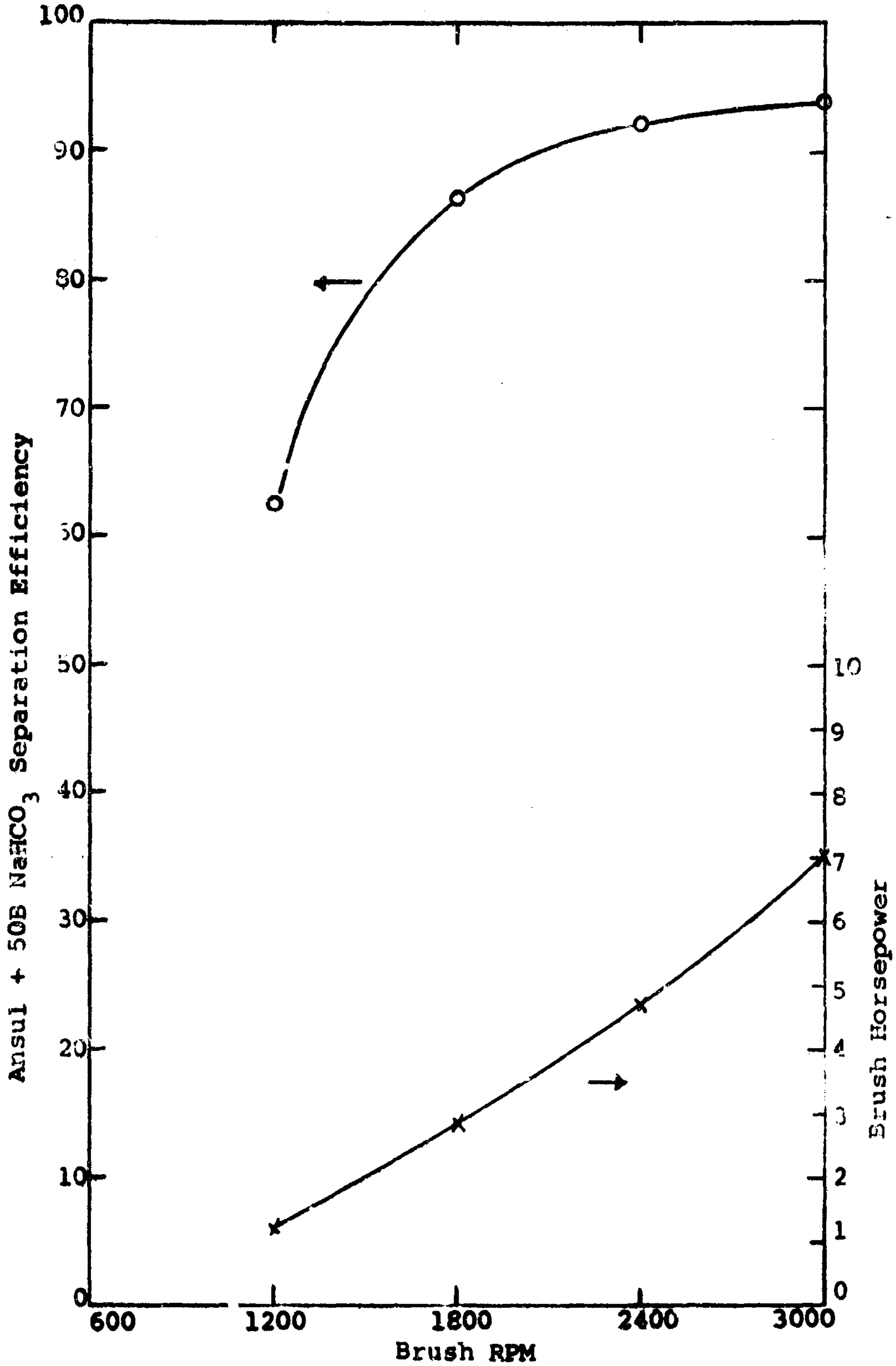

Figure 20: Brush RPM vs. Efficiency and Horsepower at 8000 CFM with Near Exhaust and 2 mm Wires (4 Brushes, 48 Wires/Row, 12 Rows/Brush)

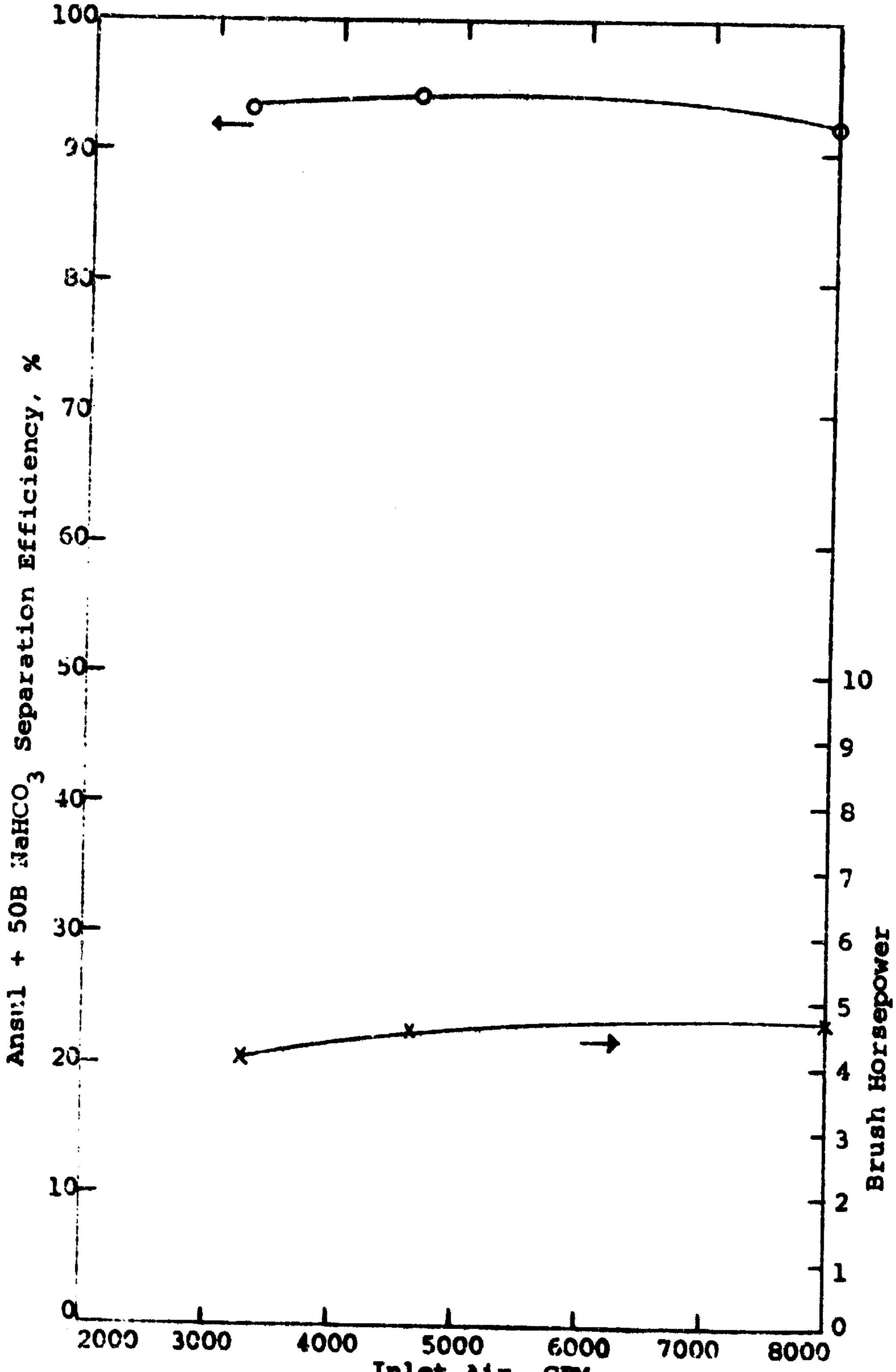

Figure 21: Inlet Air CFM vs. Efficiency and Horsepower at 2400 RPM with Near Exhaust and 2 mm Wires (4 Brushes, 48 Wires/Row, 12 Rows/Brush)

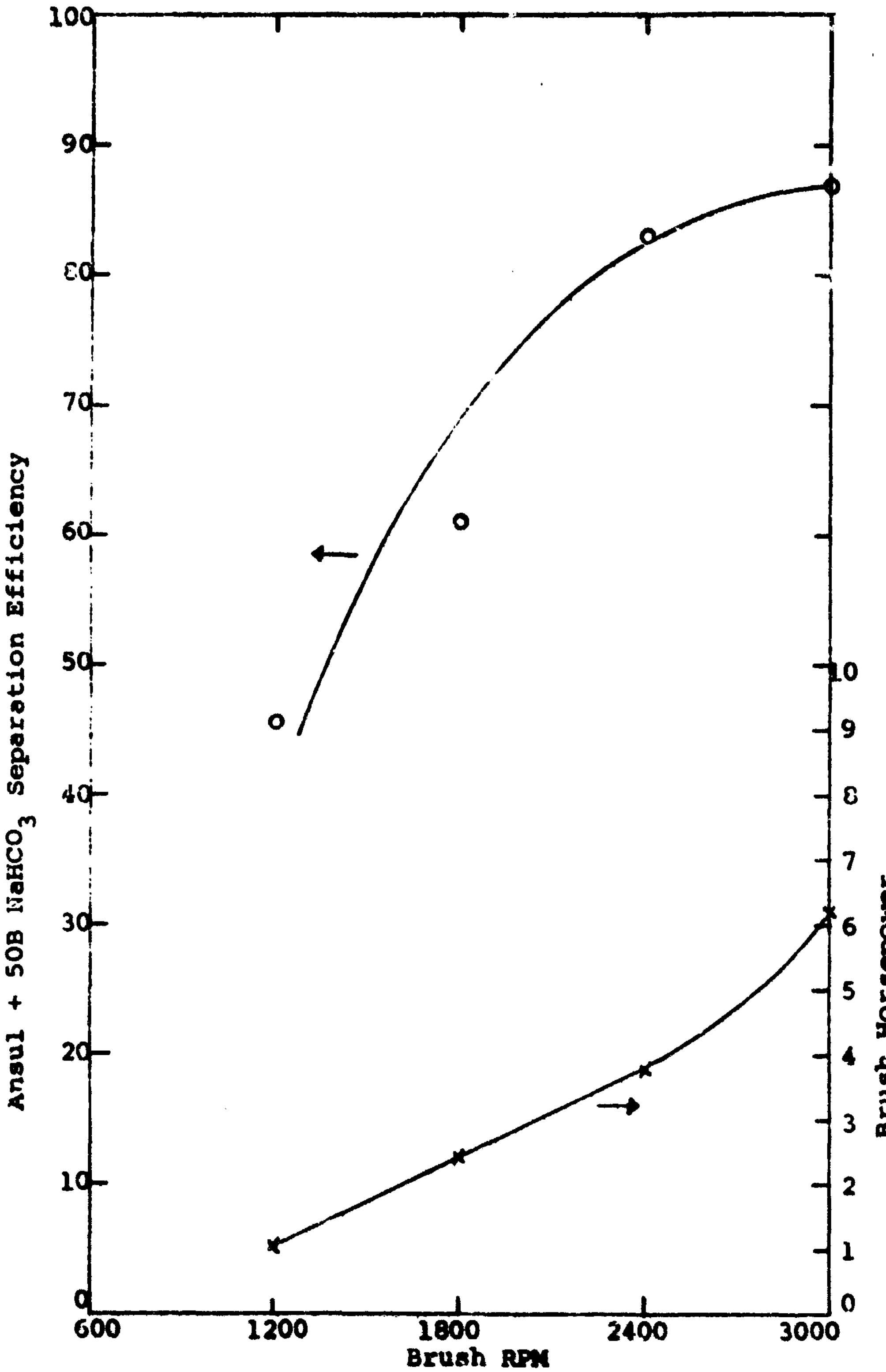

Figure 22: Brush RPM vs. Efficiency and Horsepower at 8000 CFM with Near Exhaust and 2 mm Wires (2 Brushes, 48 Wires/Row, 12 Rows/Brush)

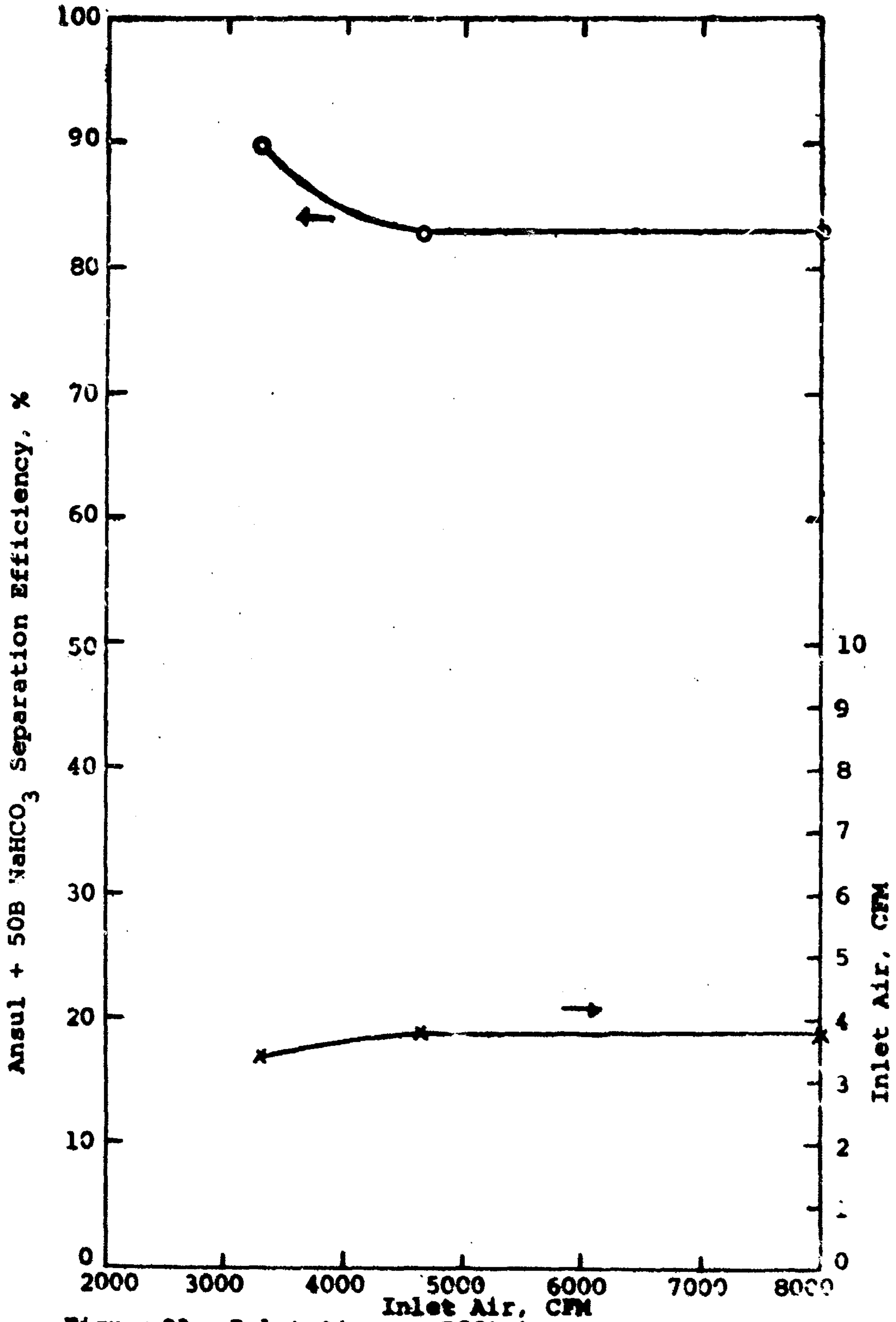

Figure 23: Inlet Air vs. Efficiency and Horsepower at 2400 RPM with Near Exhaust and 2 mm Wires (2 Brushes, 48 Wires/Row, 12 Rows/Brush)

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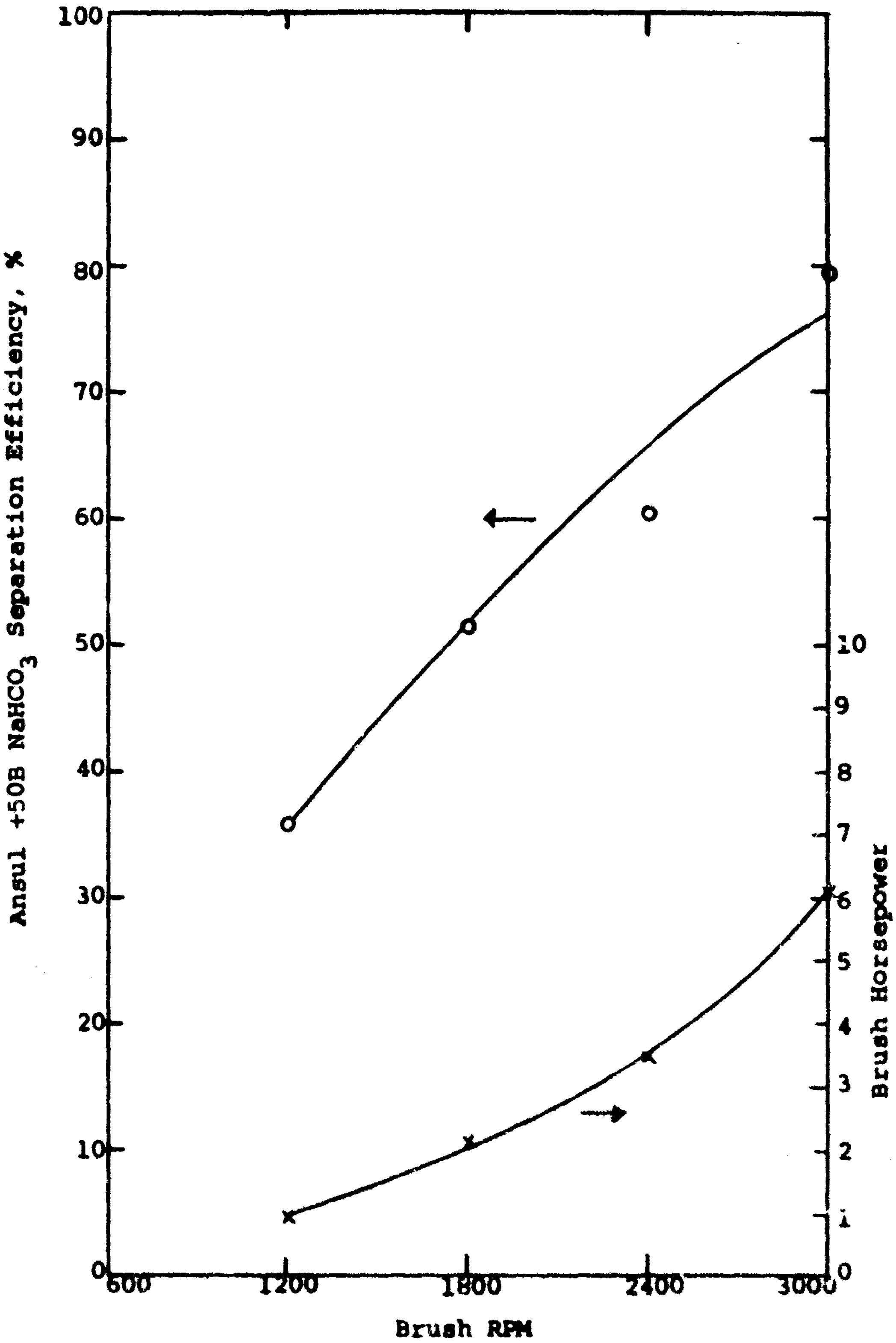

Fig. 24: Brush RPM vs. Efficiency and Horsepower at 8000 CFM with Near Exhaust and 2 mm Wires (2 brushes, 24 wires/row, 12 rows/brush)

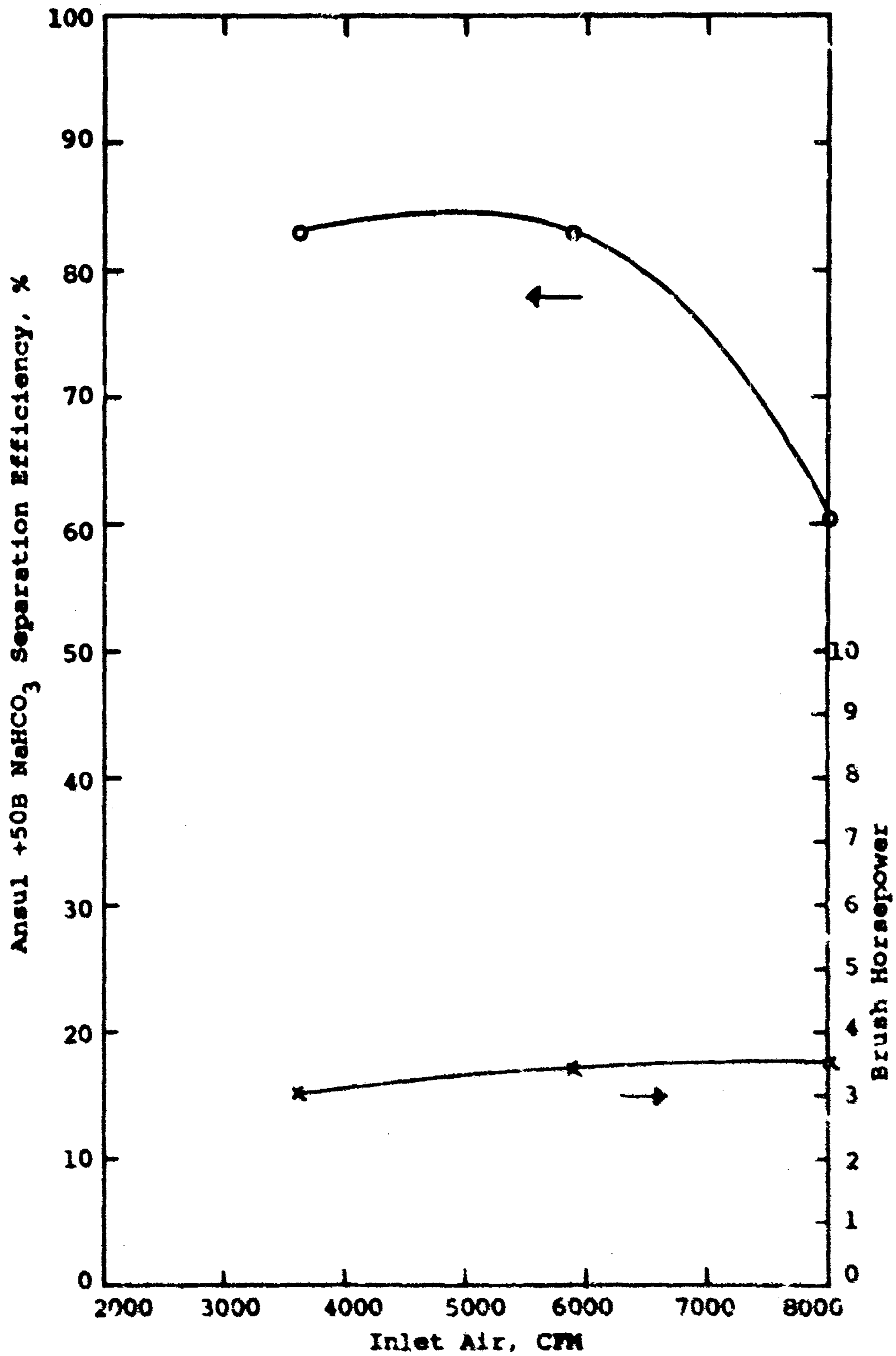

Fig. 25: Inlet Air CFM vs. Efficiency and Horsepower at 2400 RPM with Near Exhaust and 2 mm Wires (2 brushes, 24 wires/row, 12 rows/brush)

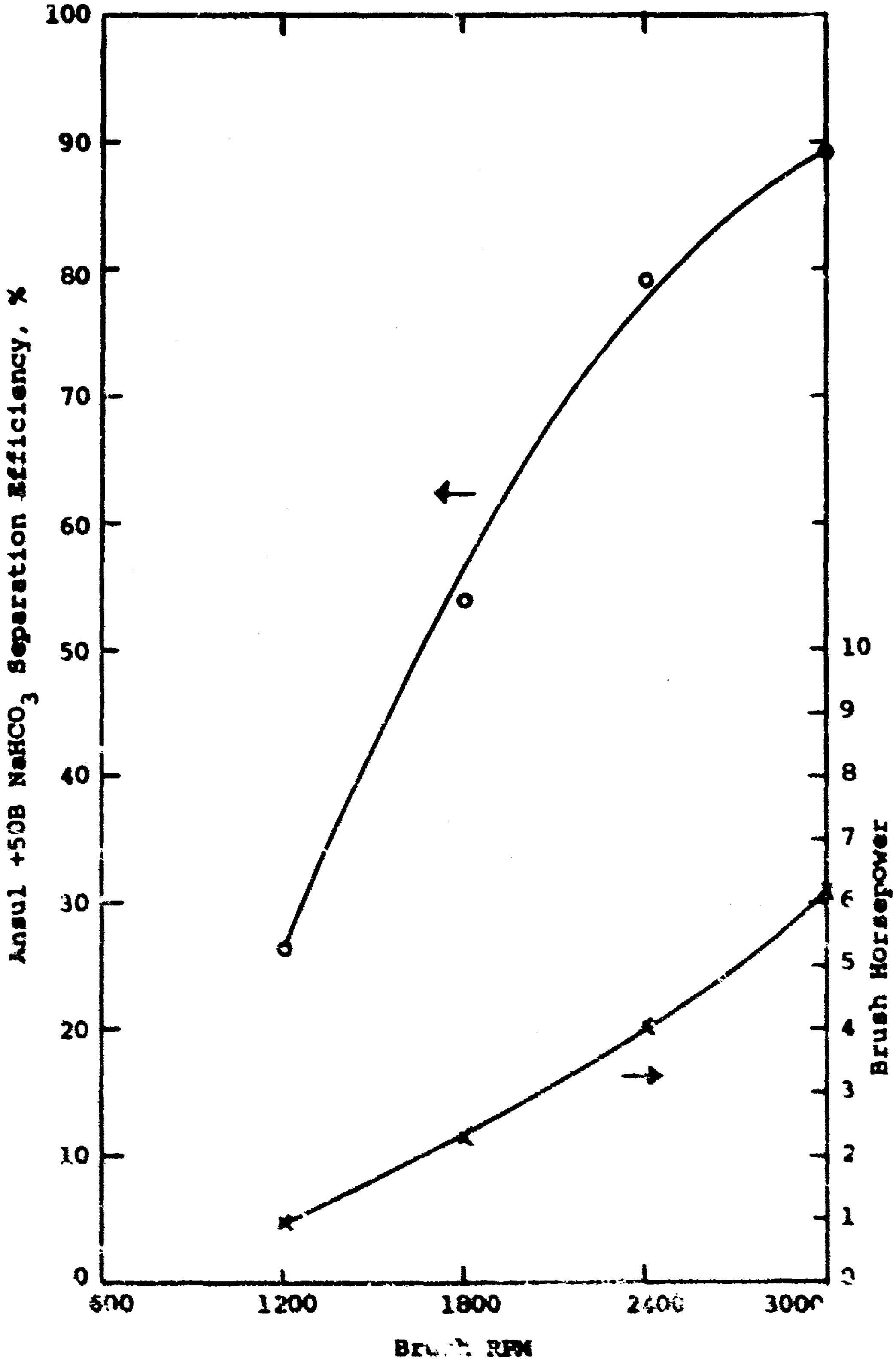

Fig. 26: Brush RPM vs. Efficiency and Horsepower at 8000 CFM with Near Exhaust and 2 mm Wire. (4 brushes, 12 wires/row, 12 rows/brush)

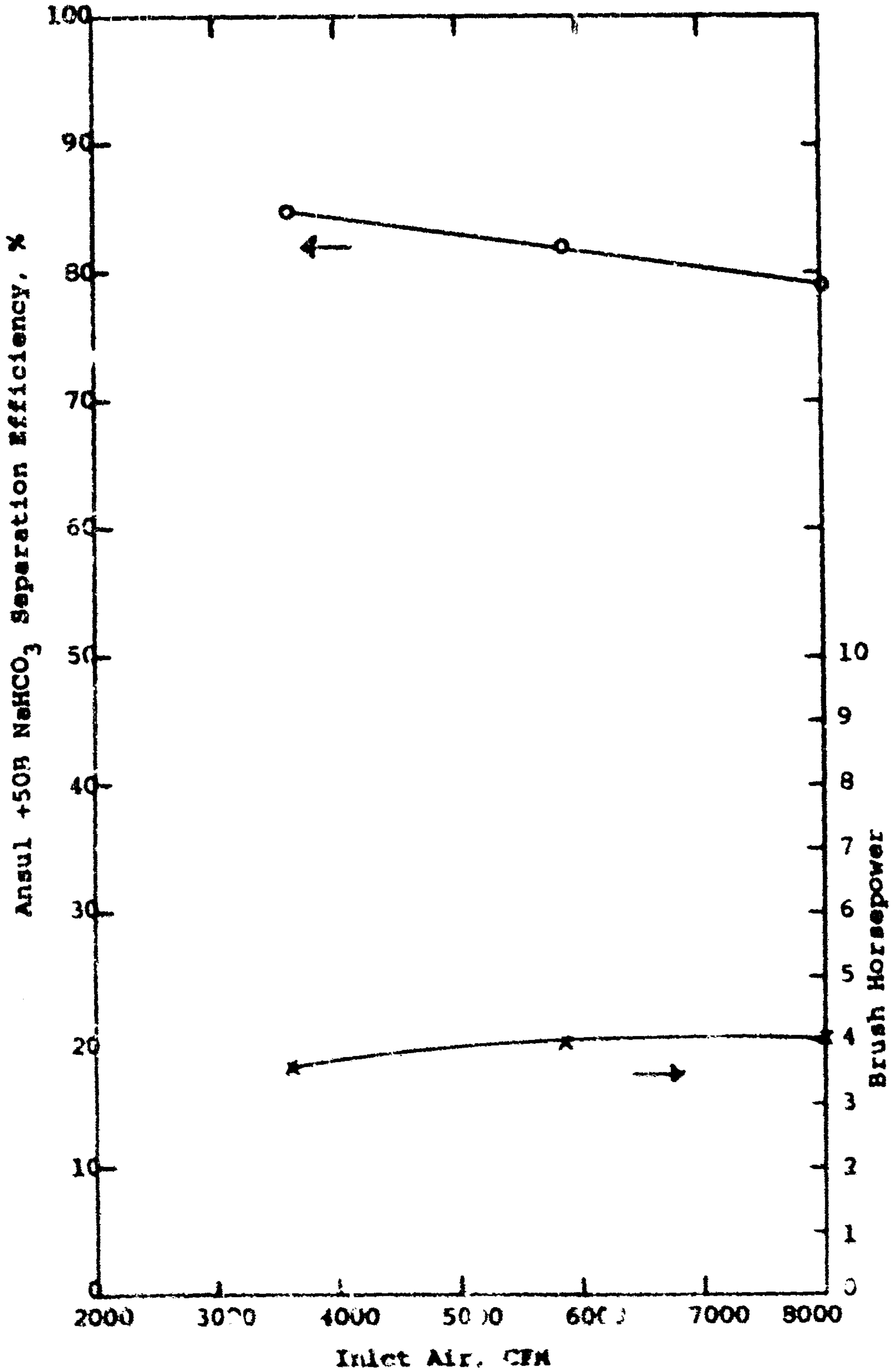

Fig. 27: Inlet Air CFM vs. Efficiency and Horsepower at 2400 RPM with Rear Exhaust and 2 mm Wires (4 brushes, 12 wires/row, 12 rows/brush)

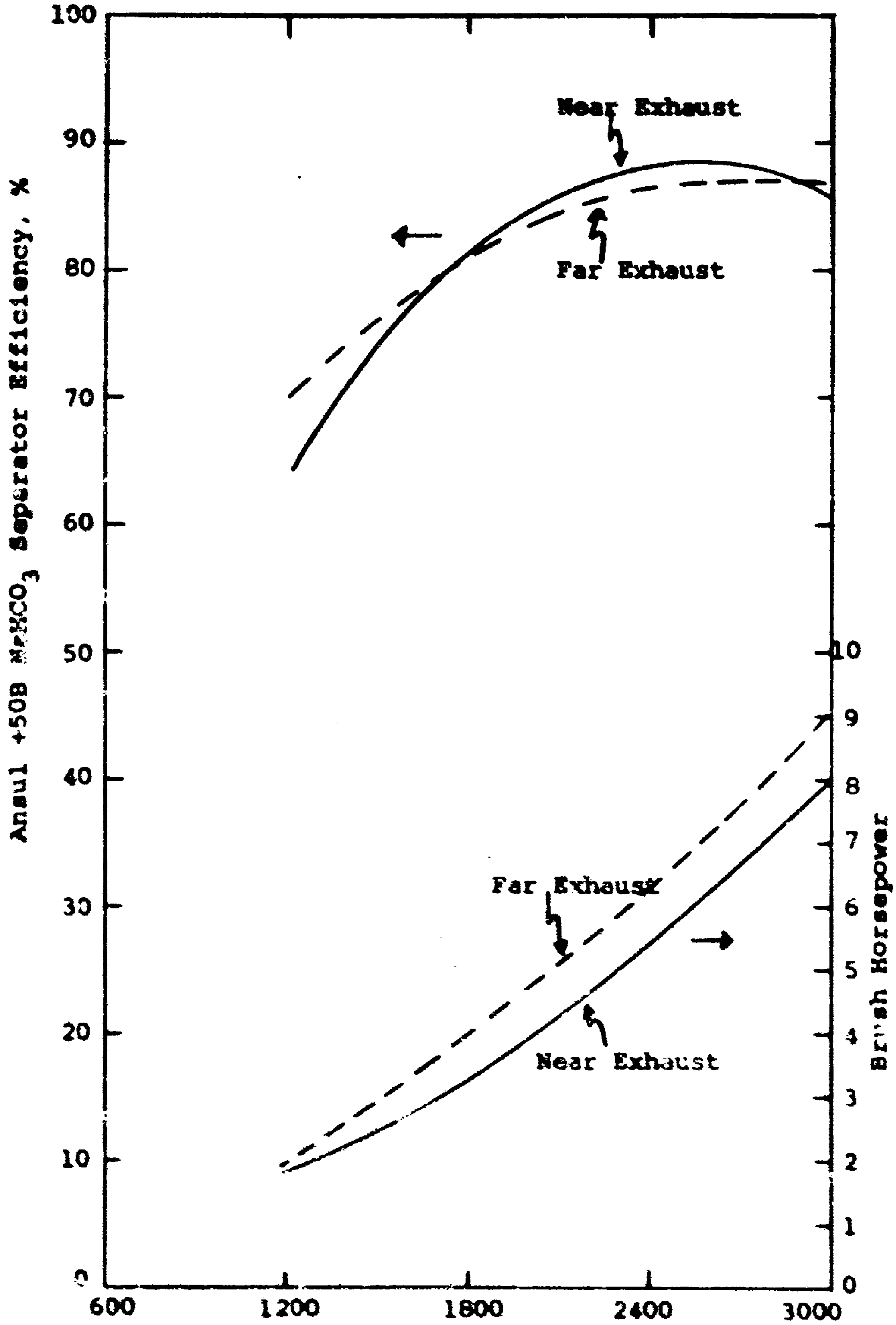

Fig. 28: Effect of Exhaust Position on Separation Efficiency and Horsepower at 8000 CFM with Flat Blades

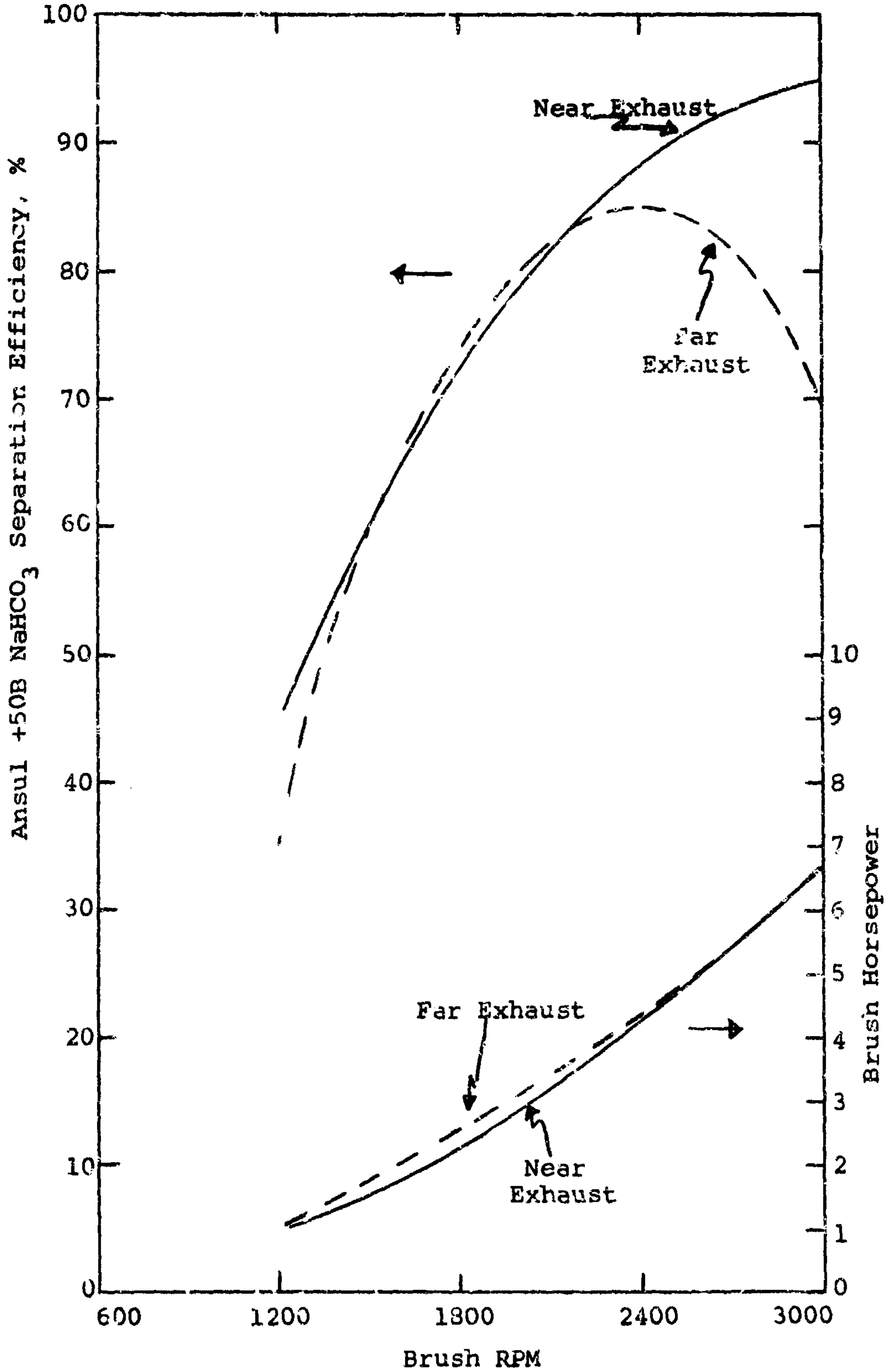

Fig. 29: Effect of Exhaust Position on Separation Efficiency and Horsepower at 8000 CFM with 1 mm Wires (4 brushes, 48 wires/row, 12 rows/brush)

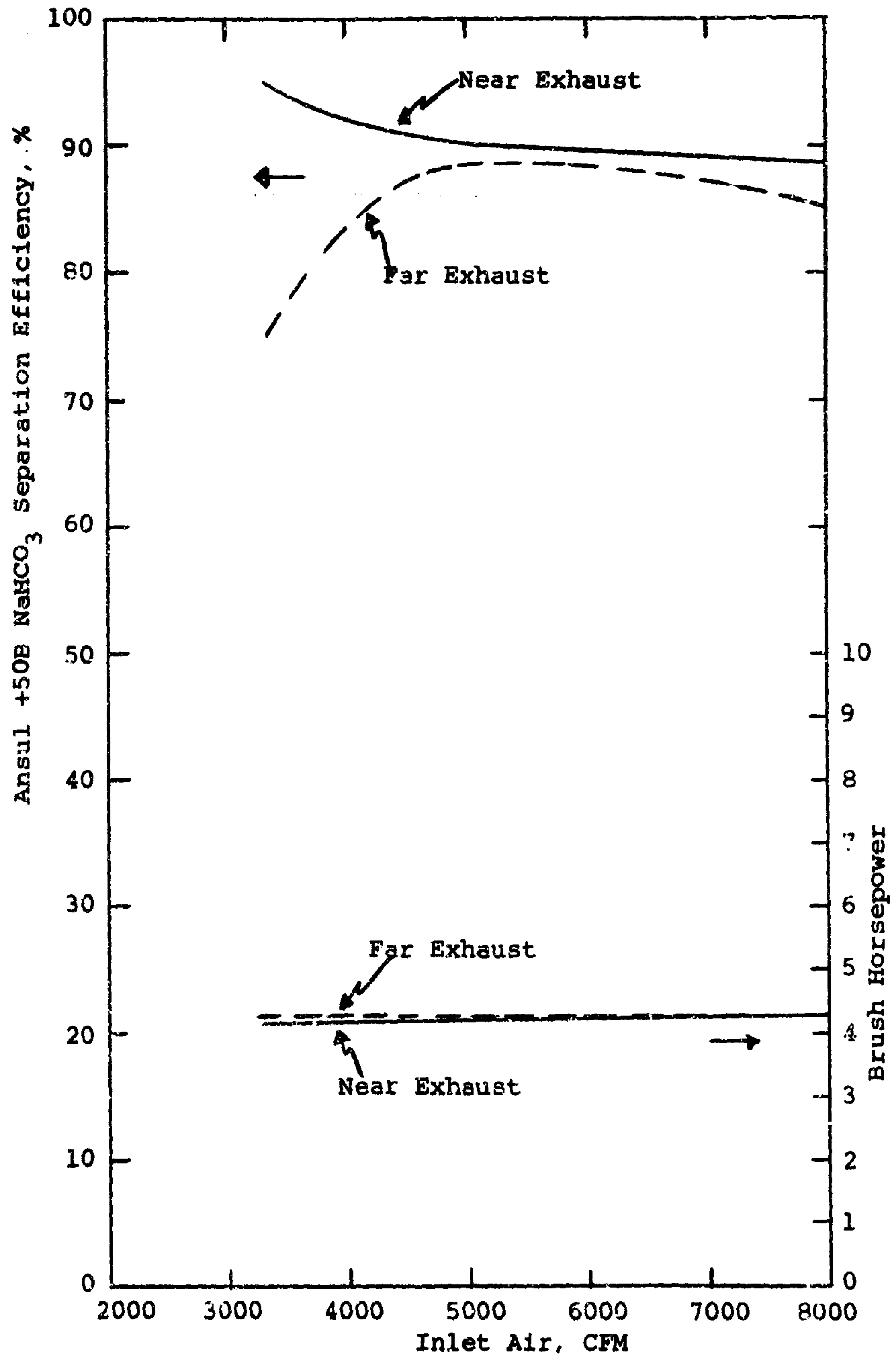

Fig. 30: Effect of Exhaust Position on Separation Efficiency and Horsepower at 2400 RPM with 1 mm Wires (4 brushes, 48 wires/row, 12 rows/brushes)

position was again superior, especially as the inlet air volume was reduced. No significant difference in brush horsepower was noted with regard to the effect of exhaust position.

It is believed that turbulence downstream of the brushes in the region ahead of the exhaust annulus worked against any improvement in separation efficiency that might have been possible with the longer residence time. Therefore, any additional separation length must be filled with additional brushes to take advantage of a longer residence time. For the above reasons, all subsequent tests were run with the exhaust annulus in the near position, i.e., with Part C614 in place so that the clean and dirty airstreams were separated immediately after the trailing brush as shown in assembly drawing E600 of Appendix A. Note also that in all tests with less than the full complement of four brushes, the forward brushes were removed so that the distance from the trailing brush to the exhaust annulus was kept constant.

2. Centrifugal Contribution

The effect of centrifugal separation as opposed to separation by impaction was examined through the use of flat blades and 1 mm diameter wires. The flat blades, Part C605 of Appendix A, were 1.875-in wide, and twelve blades were mounted on each of four brush hubs for a total projected width of 4 x 12 x 1.875 x 25.4 = 2282 mm. The use of flat blades rather than wires reduced the influence of impaction as a separation mechanism since the impaction parameter decreases as the width of a collecting surface increases. The comparative tests with 1-mm wire brushes utilized four brushes with 48 wires/row and 12 rows/brush for a total projected width of 4 x 48 x 12 x 1 = 2305 mm, or essentially the same as that presented by the flat-blade brushes.

The blade versus wire comparative tests are shown in Fig. 31. It appears that at brush speeds below 2400 RPM and at an airflow of 8000 CFM, the flat blades are more effective than the wire brushes, probably due to a more efficient transfer of rotational velocity to the incoming air. However, at brush speeds above 2400 RPM, the separation efficiency of the flat-blade brush has decreased from its maximum of about 88%, whereas the separation efficiency of the 1-mm wire brush continued to rise beyond 2400 RPM and reached 95% at 3000 RPM. In the region of maximum separation efficiency, it appears that while centrifugal separation is a major factor, impaction effects become increasingly important and supplement the primary centrifugal effect. An added bonus is the fact that the wire brush configuration takes about 15% less horsepower at 3000 RPM in spite of the much higher separation efficiency. The detrimental effects of the far exhaust position do not permit a valid comparison of centrifugal effects for this mode of operation.

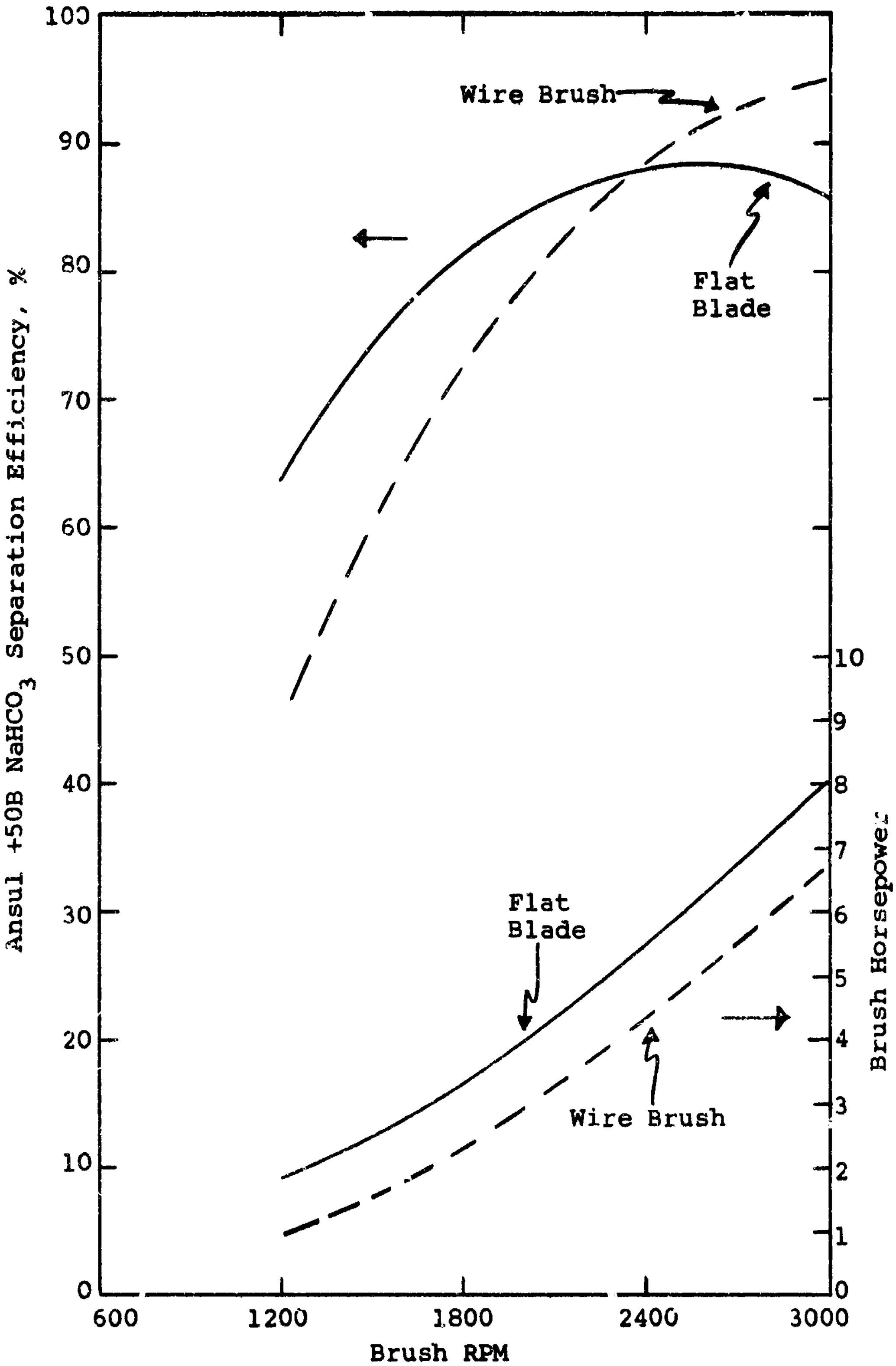

Fig. 31: Centrifugal Effect (Flat Blades vs. 1 mm Wires) on Separation Efficiency and Horsepower at 8000 CFM (4 brushes, 48 wires/row, 12 rows/brush)

It should be noted that while we have attempted to distinguish between centrifugal and impaction effects in these experiments with the flat blades, this was done only to a degree since even the blades will allow much impaction of particles in the size range of 50 μm. For example, the 50% impaction size for a spherical particle of $NaHCO_3$ at a six inch radius on a 1.875-in. wide flat-plate at 3000 RPM is only 16 μm as calculated from the data of Langmuir and Blodgett.[a] In spite of this shortcoming, the flat-blade tests do show the superiority of the wire brush in obtaining higher separation efficiencies at lower power consumption.

3. Axial and Radial Spacing Betweeen Wires

The effects of wire spacing on brush separator performance were evaluated in a series of tests in which the radial spacing (wires/row) and the axial spacing (number of brushes) was varied for both 1-mm and 2-mm wire brushes at various test conditions, Figs. 32 through 35. In the tests with the 1-mm wire brushes, at a constant total projected wire width of 1152 mm, Figs. 32 and 33, the differences in efficiency and horsepower are slight and are not significant.

The method of wire spacing does become important when 2-mm wire brushes at a constant total projected wire width of 1152 mm are used, Figs. 34 and 35. As the brush RPM increases and separation efficiency rises, Fig. 34, the four-brush configuration becomes increasingly superior to the corresponding two-brush configuration. A similar situation occurs when the brush speed is kept constant at 2400 RPM and the inlet-air CFM is increased, Fig. 35. As the inlet-air volume increases from 6000 CFM to 8000 CFM, separation efficiency falls off rapidly for the two-brush configuration, whereas the four-brush configuration is much more stable in performance. Slightly more horsepower is required for the four brush configuration, perhaps due to a more efficient transfer of energy to the inlet air resulting in a faster spin imparted to the air. The faster spin imparted to the air passing through the separator would then enhance the centrifugal separation mechanism.

While axial versus radial wire spacing does not appear to be an important parameter for 1-mm wires in the tests conducted, it is an important parameter when 2-mm wires are used. As will be noted later, structural and abrasive considerations favor the use of the larger wires. The significance of the results of the wire spacing tests is that 2-mm wires added to a configuration in the

[a] Chemical Engineer's Handbook, J. H. Perry, Ed., 3rd Edition, p. 1022.

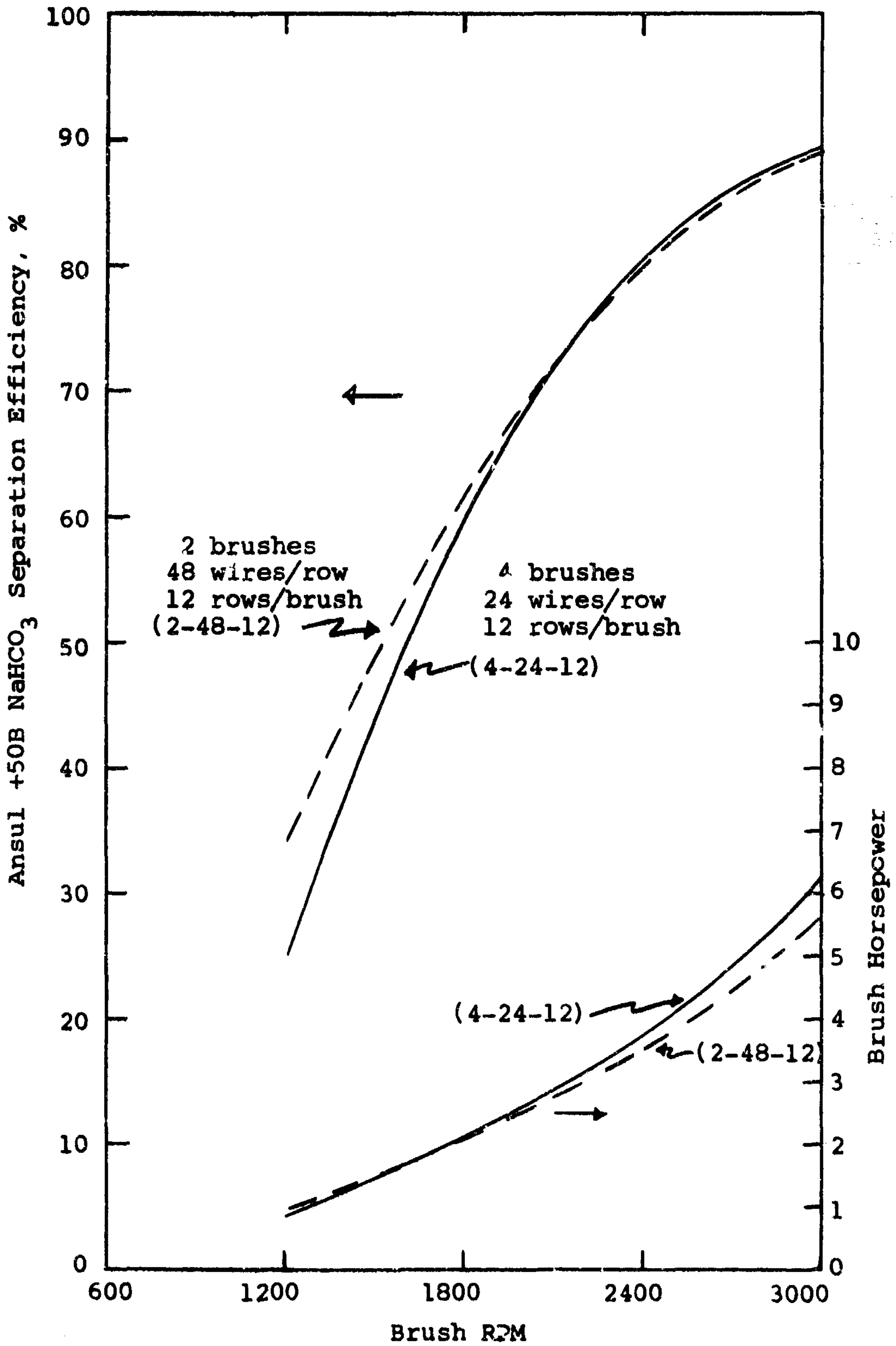

Fig. 32: Effect of Spacing of 1 mm Wires on Separation Efficiency and Horsepower at 8000 CFM

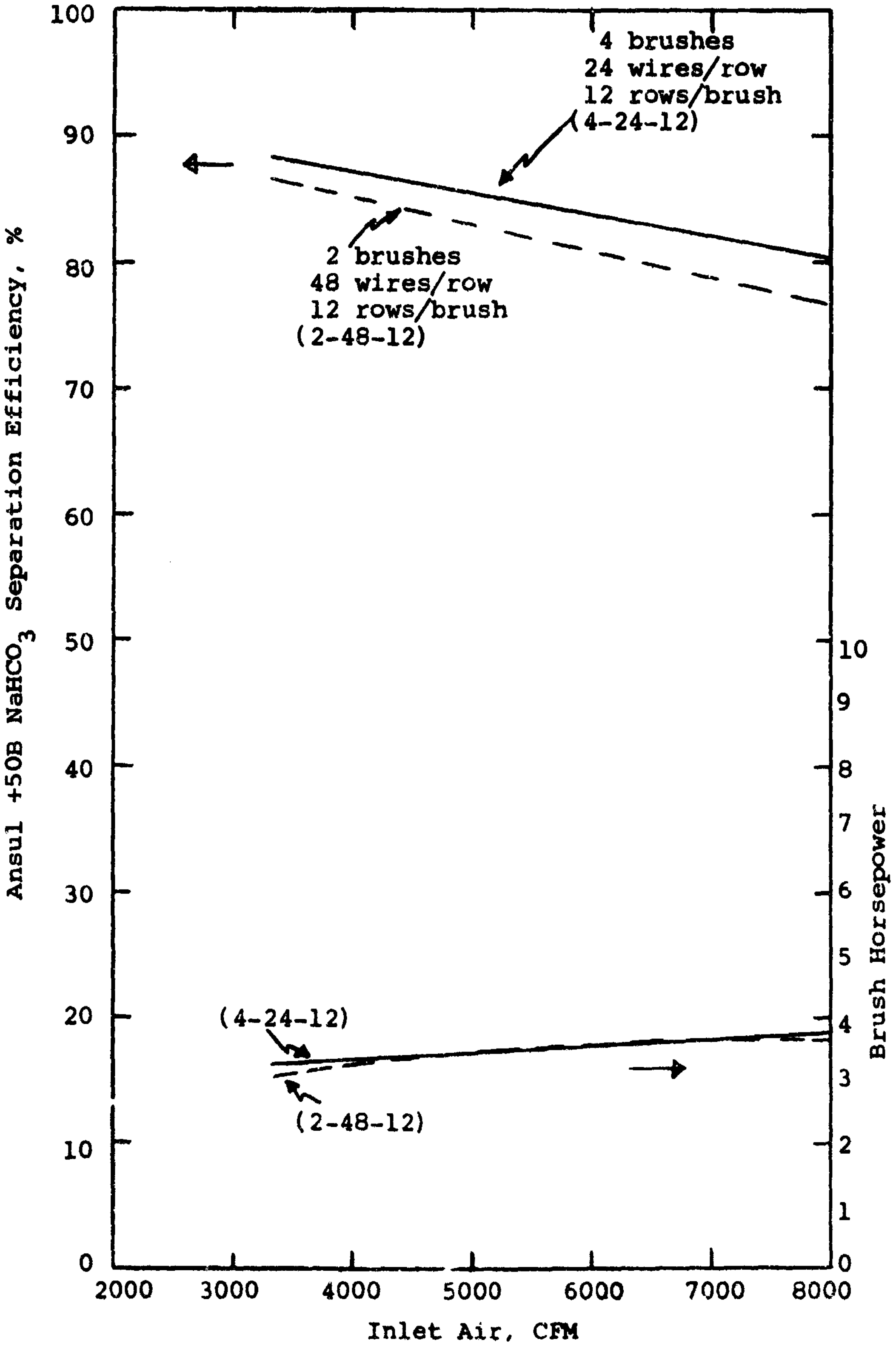

Fig. 33: Effect of Spacing of 1 mm Wires on Separation Efficiency and Horsepower at 2400 RPM

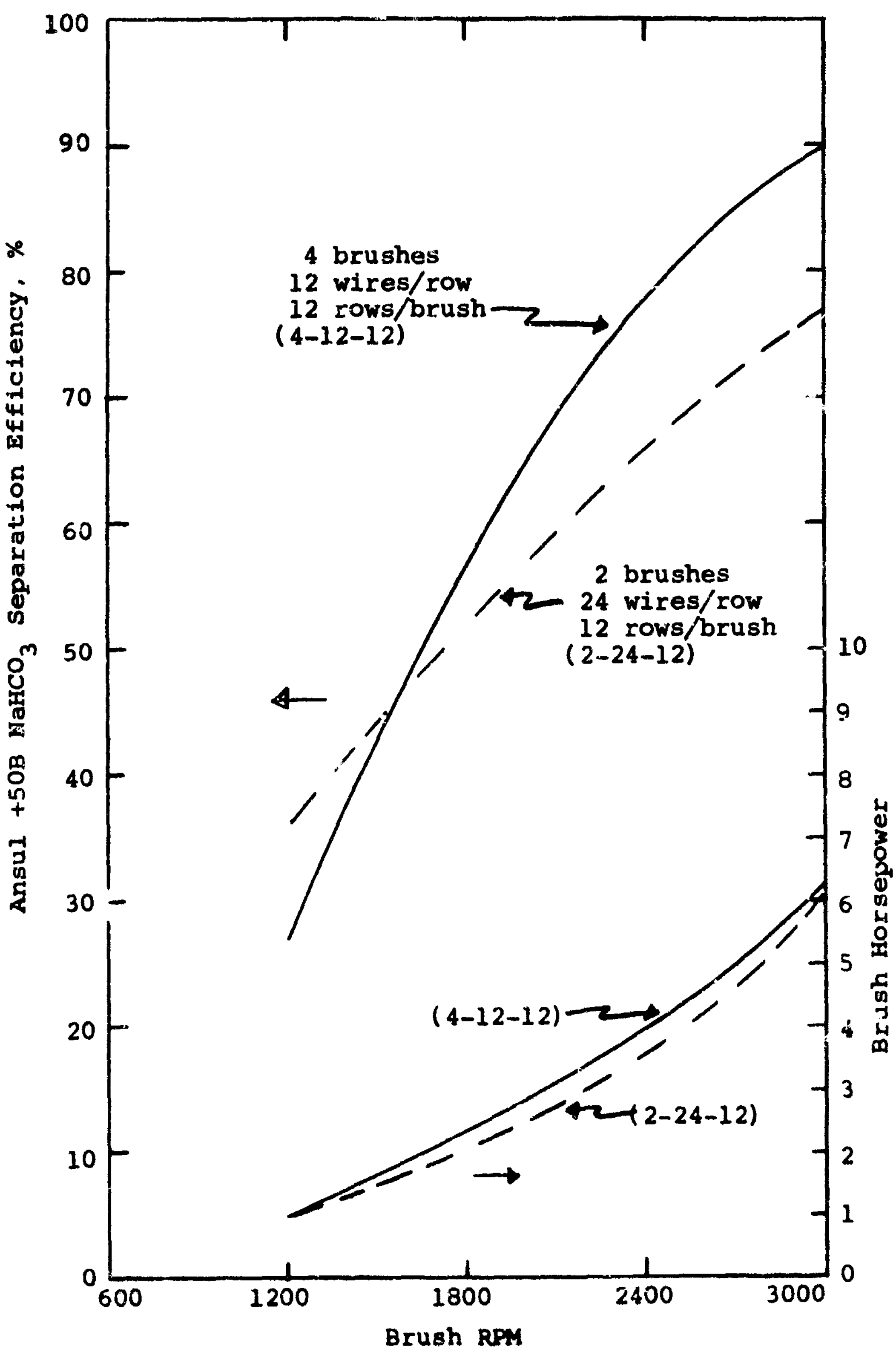

Fig. 34: Effect of Spacing of 2 mm Wires on Separation Efficiency and Horsepower at 8000 CFM

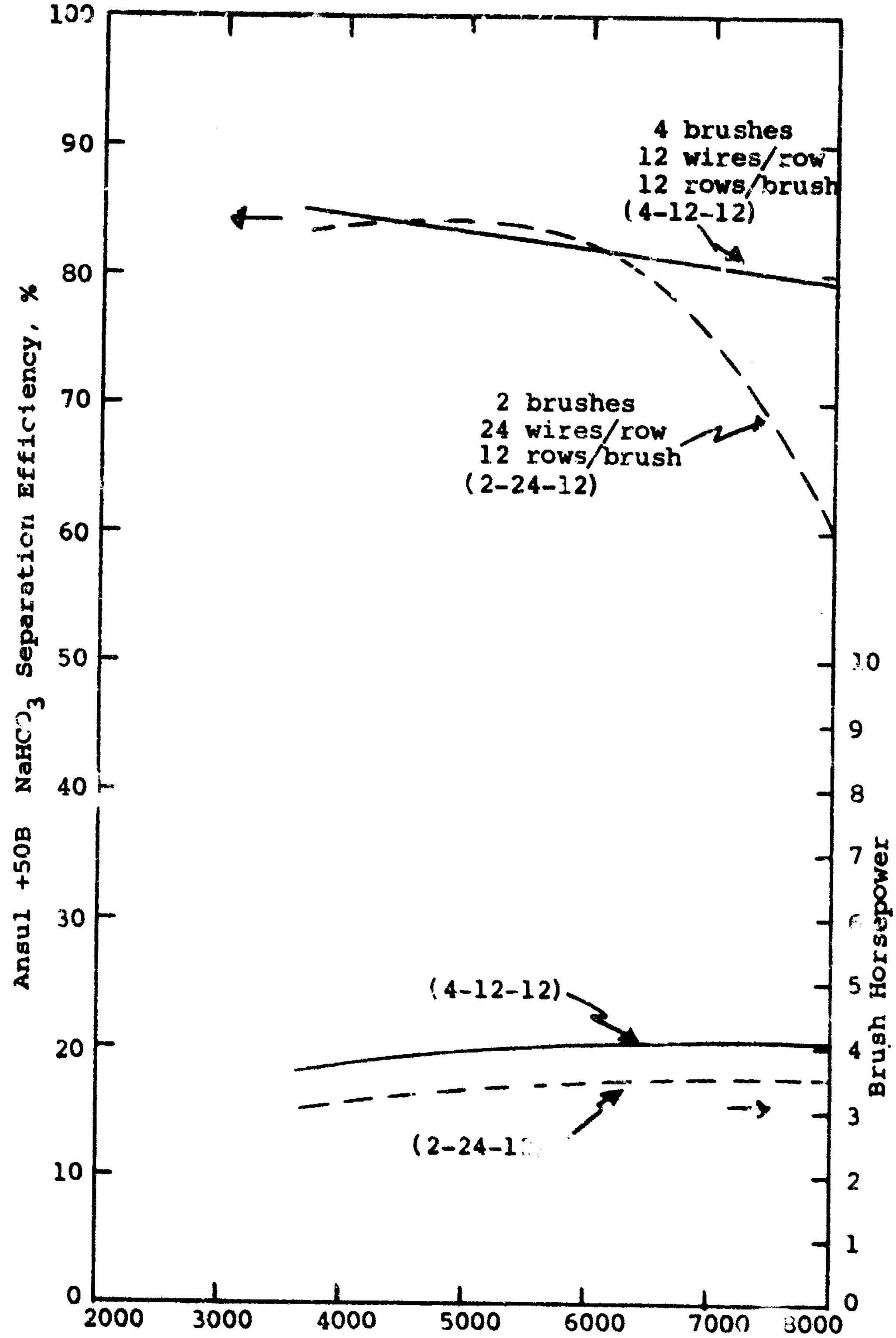

Fig. 35: Effect of Spacing of 2 mm Wires on Separation Efficiency and Horsepower at 2400 RPM

axial direction are more effective than wires added in the radial direction. Carried to an extreme, this means that given so many wires, the most efficient use of these wires would entail mounting them singly on a shaft with only one wire per row, much like the rungs on a pole ladder. The least efficient use of these wires would be to space them all in one row, much like the ribs on an umbrella. Of course, space limitations require a trade-off between these two extremes.

4. Impaction Area

The way to change the impaction area is to change the number of wires either through the radial or axial direction. As noted in the wire spacing tests discussed in the previous section, the most efficient way to add impaction area is to increase the number of brushes rather than increase the wire population on the same number of brushes. Therefore, comparative tests, Figs. 36 through 38, were conducted by varying the number of brushes (2 or 4) while keeping the number of wires per brush constant(576).

A doubling of the number of 1-mm wire brushes, Fig. 36, resulted in a 6-to 11% increase in the separation efficiency over the range of 1200-to 3000 RPM. At 3000 RPM where efficiency as usual was at a maximum, the horsepower requirements increased by 20% for four brushes as compared to two brushes. Also, at 3000 RPM, the amount of dust not removed by the separator varies inversely with the number of brushes.

Similarly for 2-mm wire brushes, Fig. 37, the separation efficiency increased by 7- to 20% over the range of 1200 to 3000 RPM when four brushes were used instead of two. About 15% more horsepower was required at 3000 RPM with four brushes. As with 1-mm wire tests, doubling the impaction area at 8000 CFM halved the dust penetration.

The effect of 2-mm wire impaction area at 2400 RPM and varying inlet air volume is shown in Fig. 38. Note that the increased impaction area is beneficial only above 3000 CFM. Apparently the number of brushes recommended for a given application will depend on the air volume requirements. While two brushes may be adequate at 3000 CFM, at 8000 CFM half of the dust which penetrates two brushes can be removed by adding two more brushes.

5. Wire Size

A series of tests were conducted with various brush combinations at various test conditions to show the effect of wire size on separation efficiency, Figs. 39 through 43. The two wire sizes examined were 1-mm and 2-mm diameter. Since a change in the wire diameter also changes impaction area if the same number of wires is retained, several combinations were examined to try to isolate the effect of wire size.

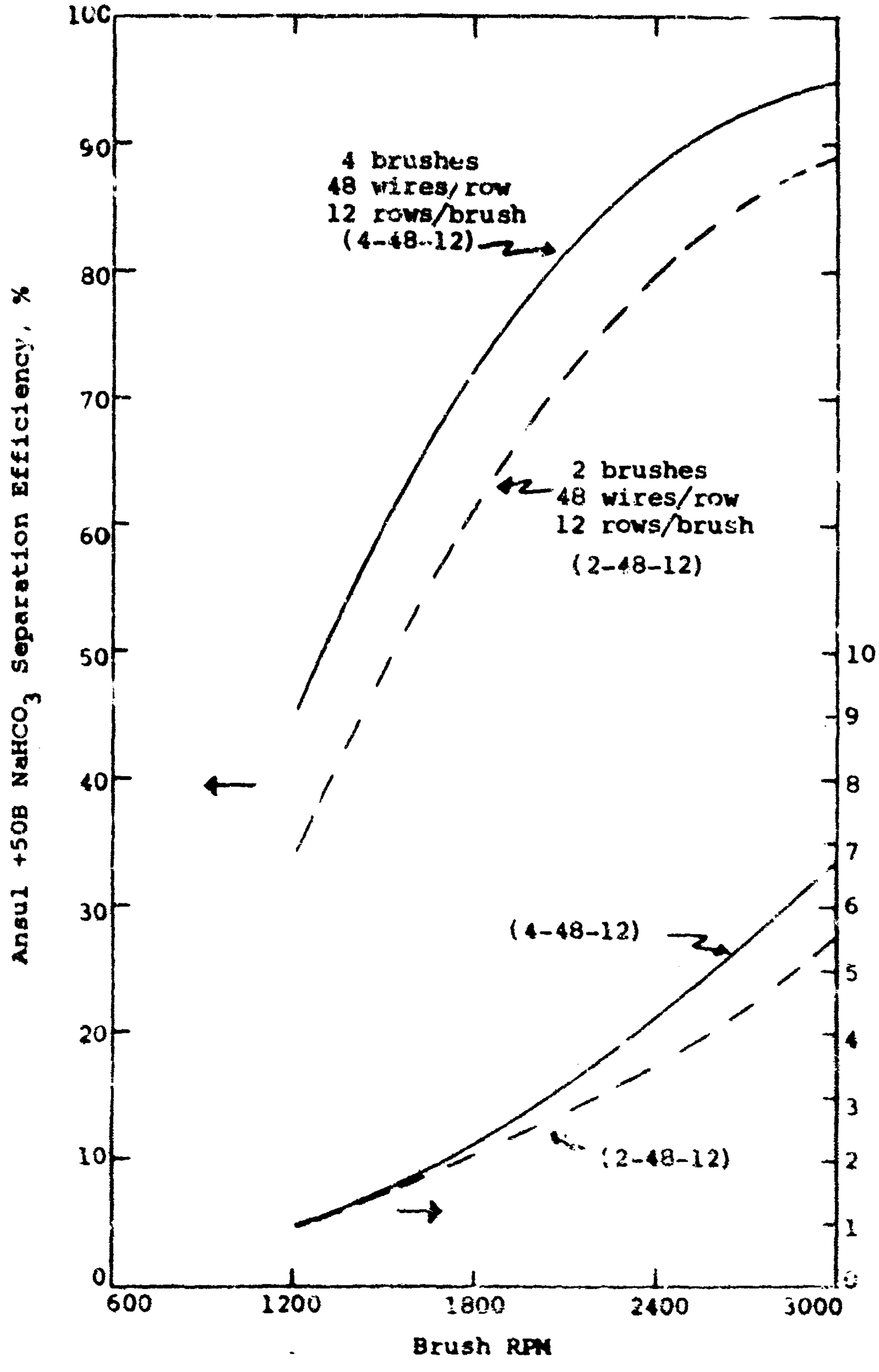

Fig. 36: Effect of Impaction Area of 1 mm Wires on Separation Efficiency and Horsepower at 8000 CFM

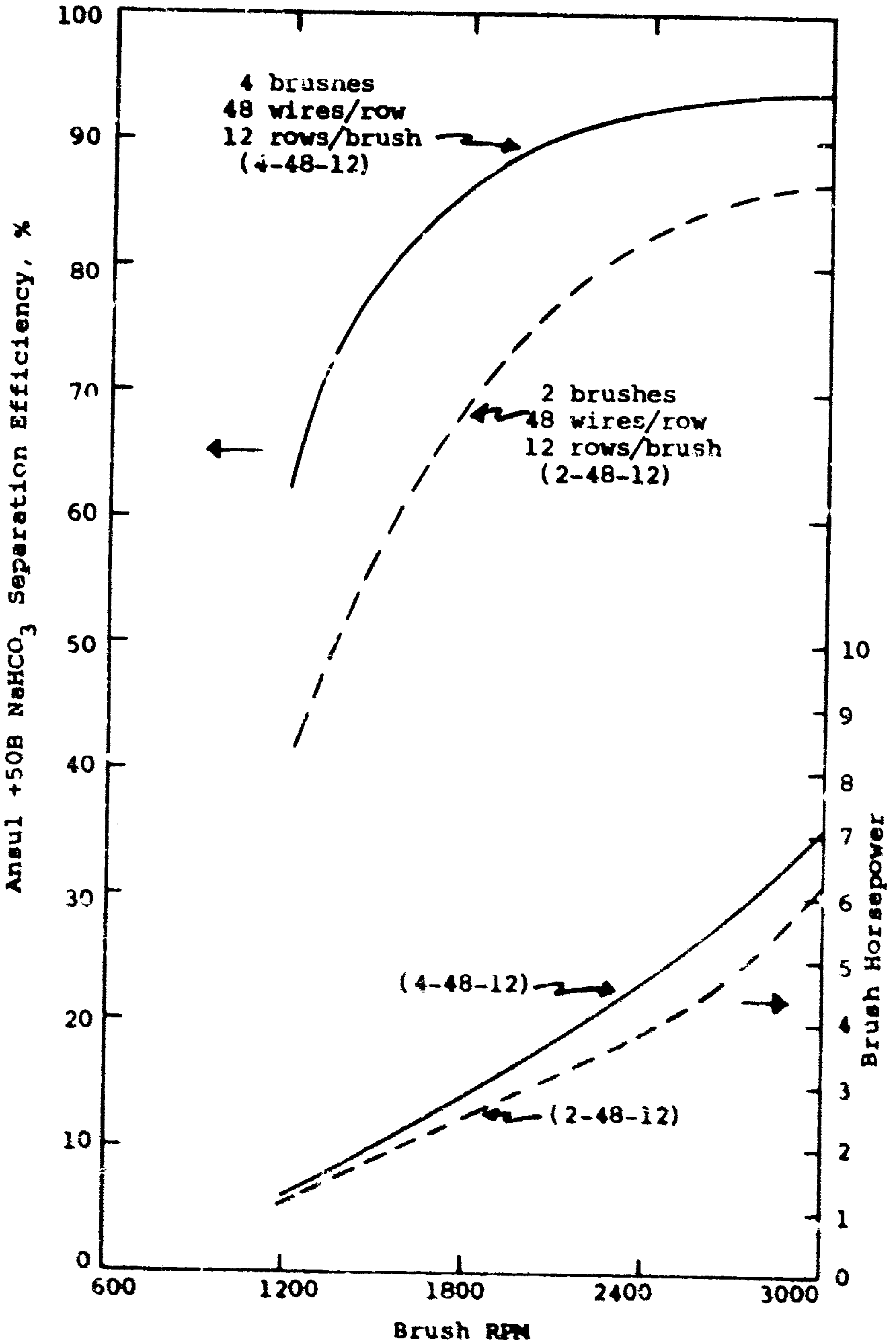

Fig. 37: Effect of Impaction Area of 2 mm Wires on Separation Efficiency and Horsepower at 8000 CFM

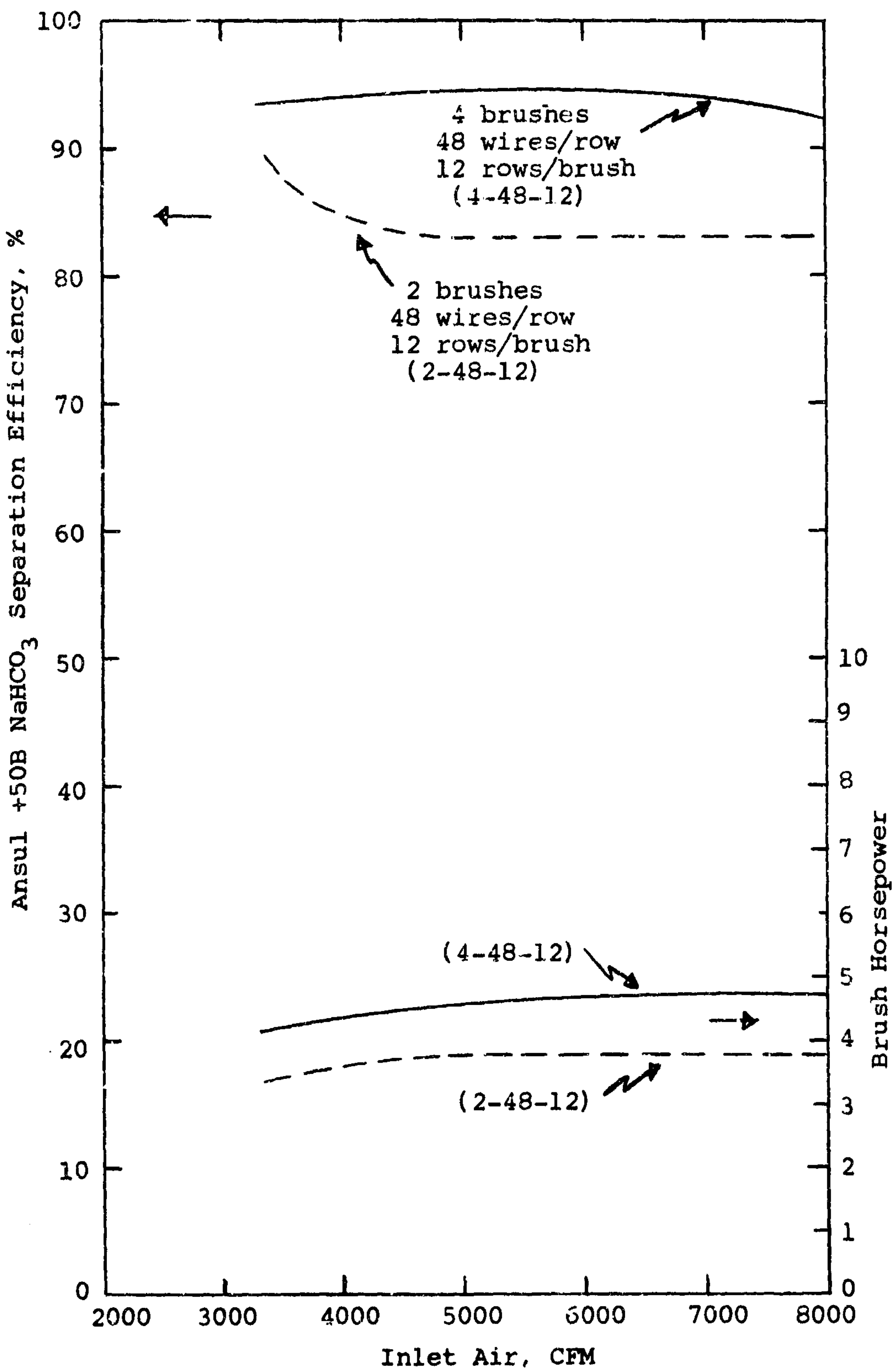

Fig. 38: Effect of Impaction Area of 2 mm Wires on Separation Efficiency and Horsepower at 2400 RPM

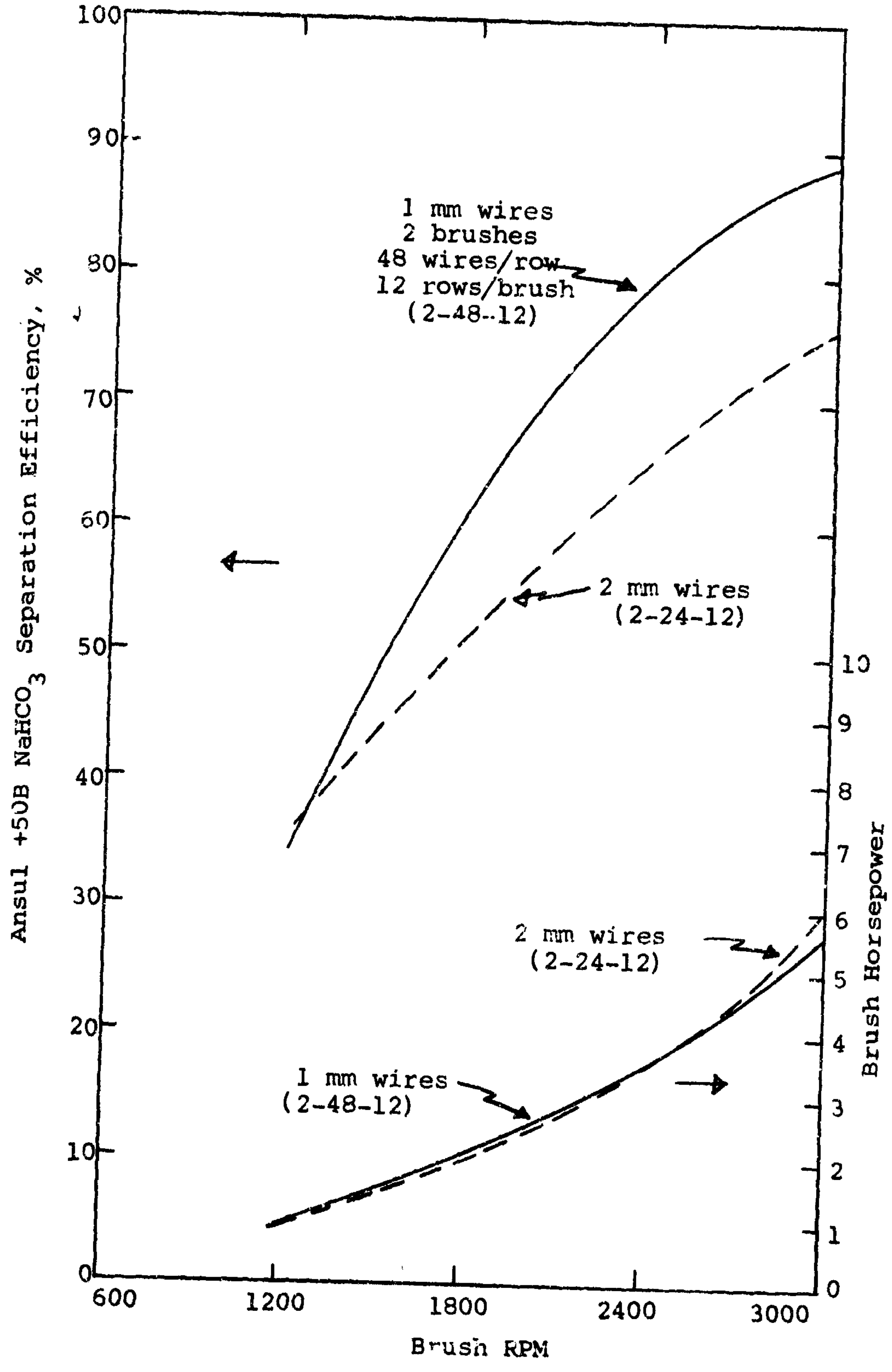

Fig. 39: Effect of Wire Size at Constant Impaction Area on Separation Efficiency and Horsepower at 8000 CFM with Two Brushes

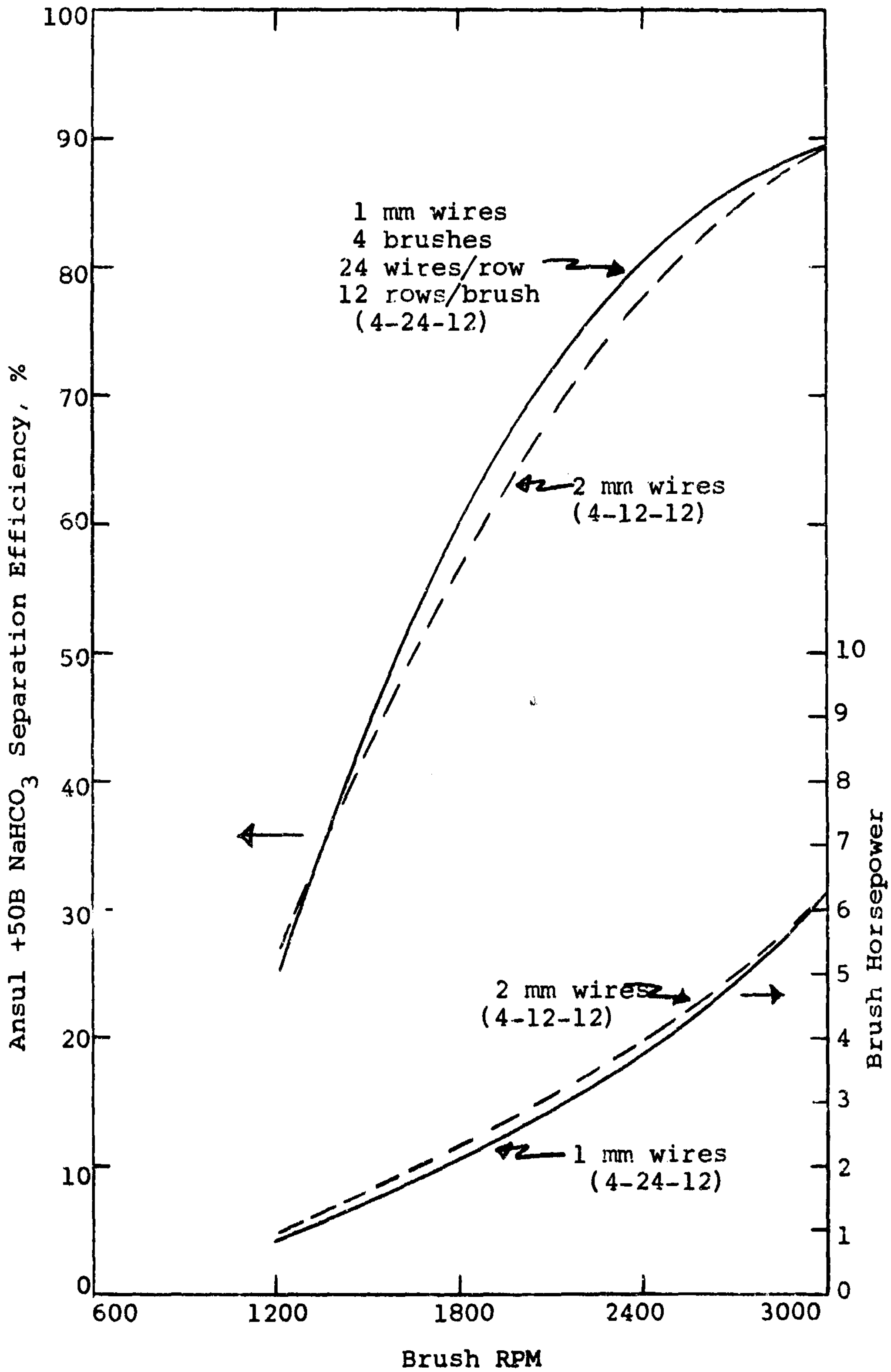

Fig. 40: Effect of Wire Size at Constant Impaction Area on Separation Efficiency and Horsepower at 8000 CFM with Four Brushes

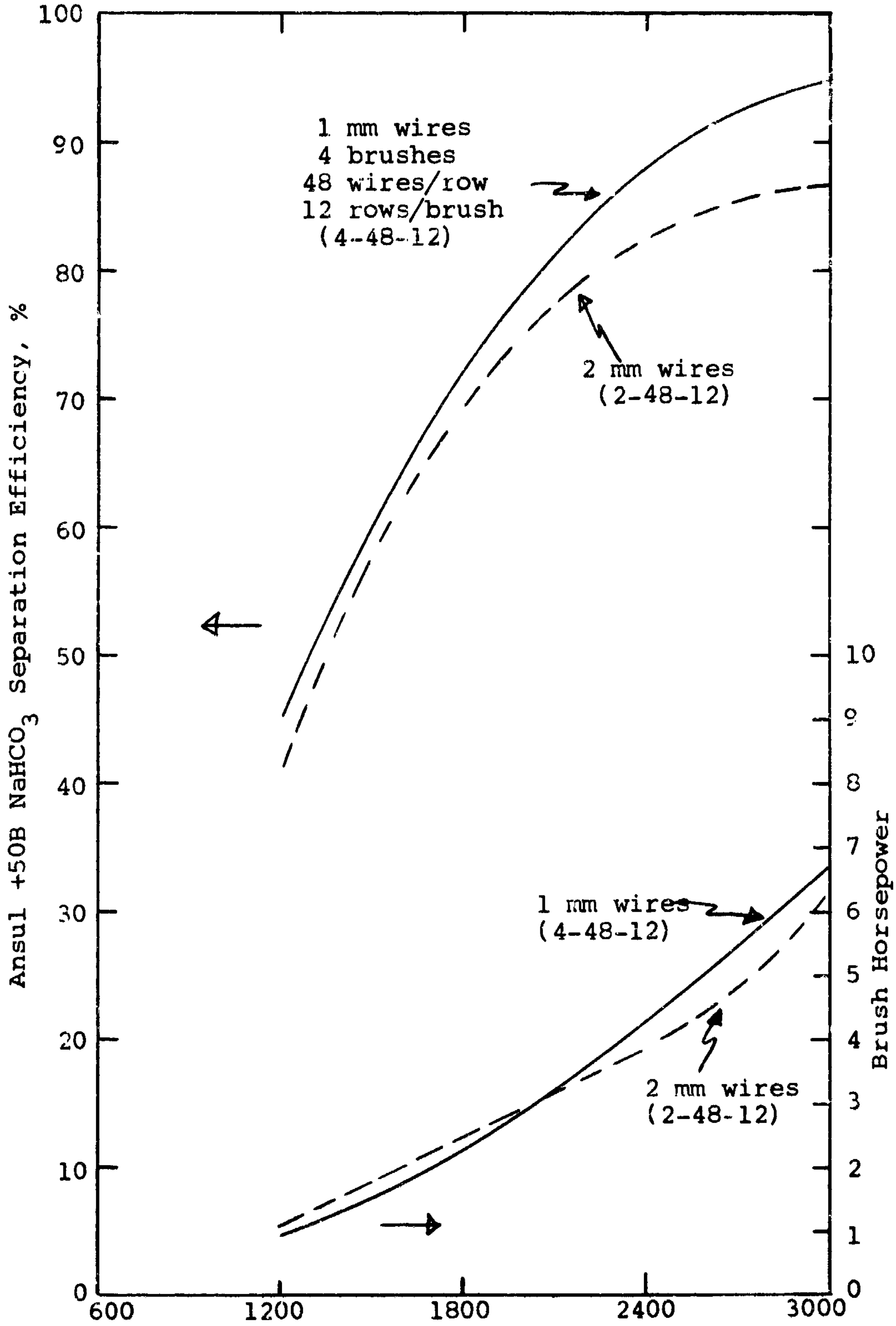

Fig. 41: Effect of Wire Size at Constant Impaction Area on Separation Efficiency and Horsepower at 8000 CFM with 48 wires/row

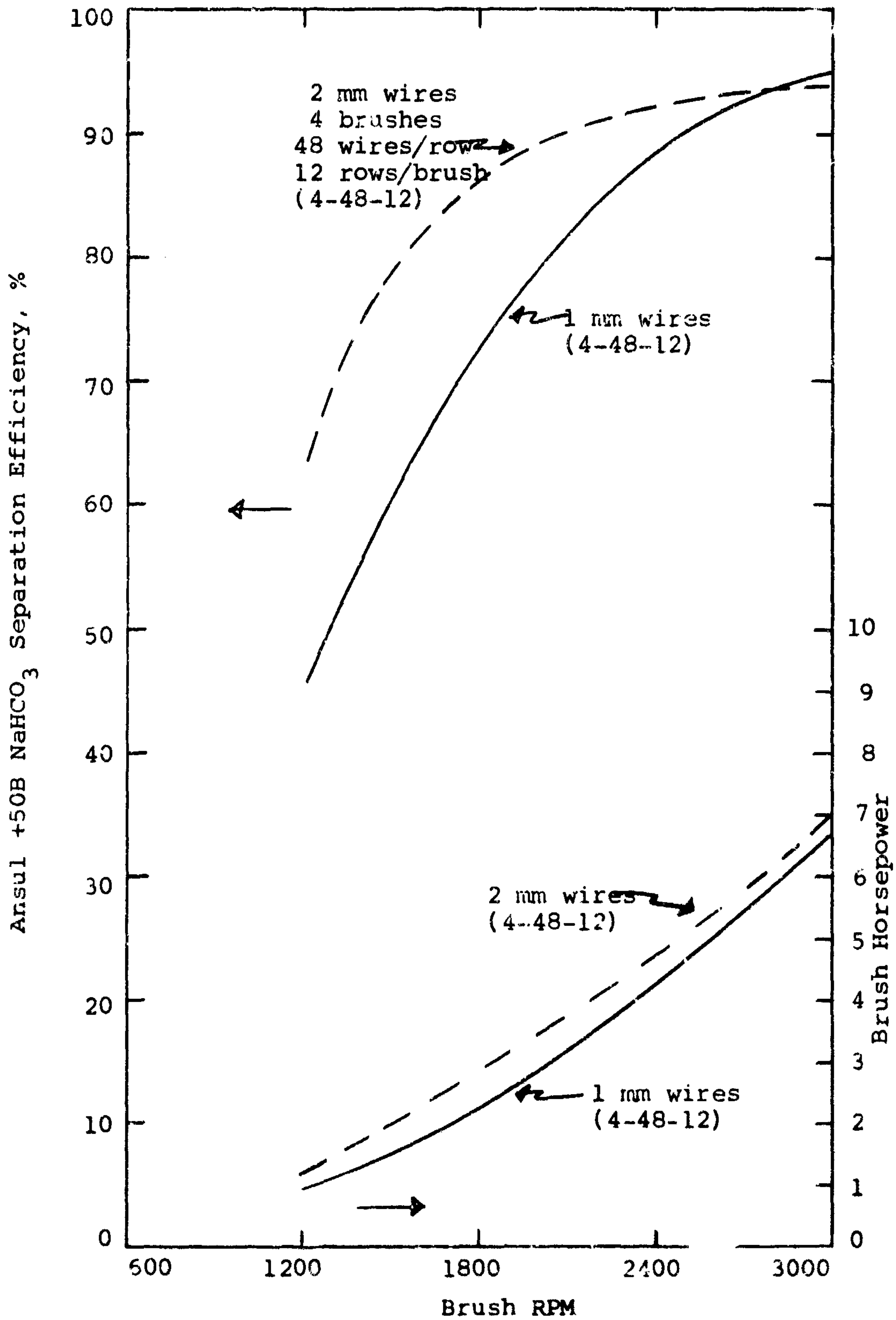

Fig. 42: Effect of Wire Size on Separation Efficiency and Horsepower at 8000 CFM with 2304 Wires

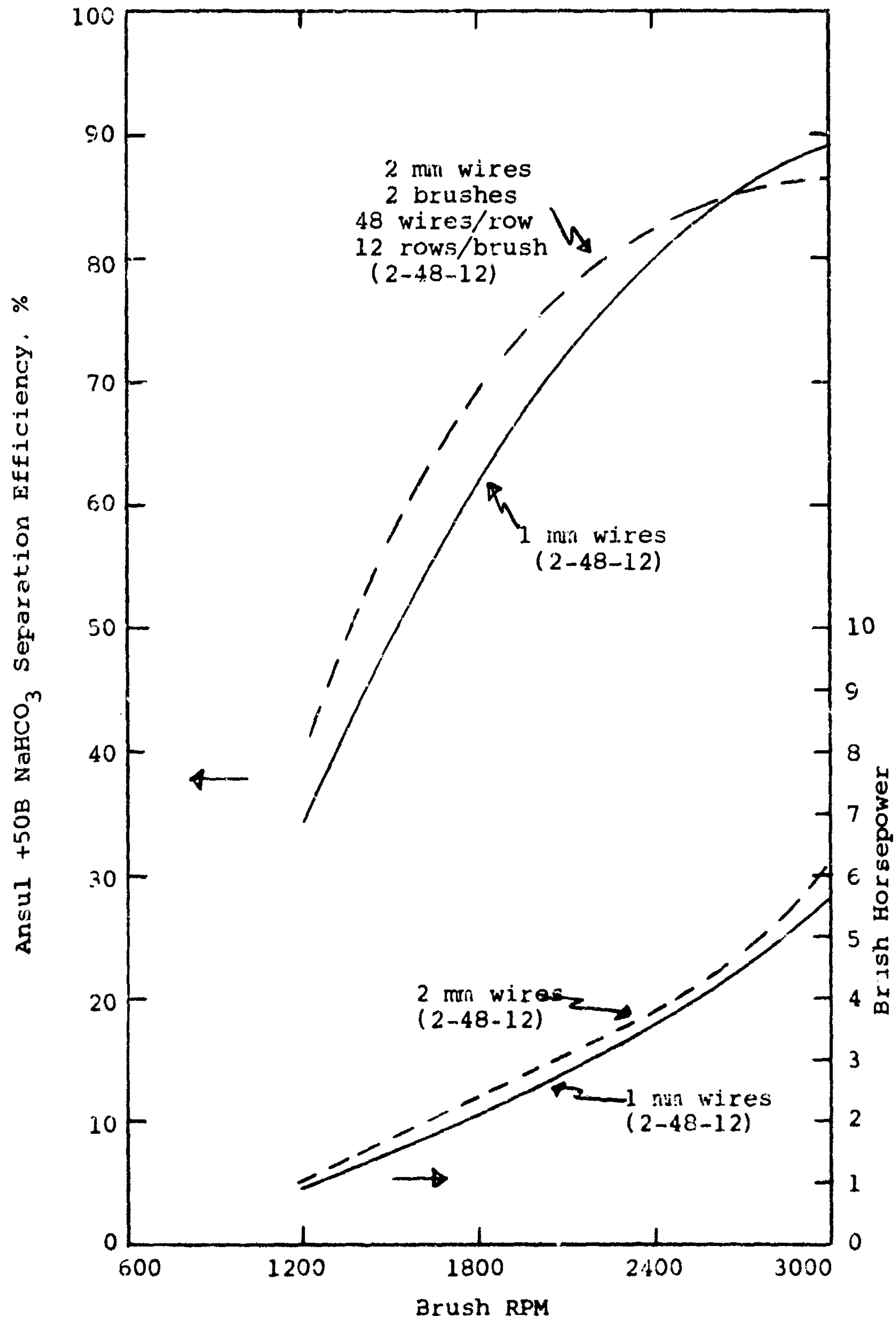

Fig. 43: Effect of Wire Size on Separation Efficiency and Horsepower at 8000 CFM with 1152 Wires

Figure 39 compares the two wire sizes at 8000 CFM with only two brushes in use. Impaction area was kept constant by halving the number of 2-mm wires from 48 wires/row to 24 wires/row. With this configuration, the 1-mm wires are clearly more effective. At 3000 RPM, the separation efficiency of the 1 mm wire configuration was 89% compared to 76% for the 2-mm wire brushes.

When four brushes were used with the same total impaction area (by halving the number of wires/row once more), no significant difference in separation efficiency or brush horsepower could be seen, Fig. 40. At 3000 RPM and 8000 CFM, both the 1-mm and 2-mm wires resulted in an 89% separation efficiency.

Still another combination was examined as shown in Fig. 41 where the full complement of 48 wires/row was used for both wire sizes, but the impaction area was kept constant by using only two of the 2-mm wire brushes compared to four of the 1-mm brushes. Here the 1-mm wire brushes are more effective with the separation efficiency approaching 95% at 3000 RPM compared to 87% for the 2-mm wire brushes. Below 2000 RPM, the differences were not significant.

For the tests depicted in Fig. 42, the full complement of four brushes, 48 wires/row, and 12 rows per brush with a total of 2,304 wires was used. This meant that the number of wires was kept constant rather than the impaction area. The 2-mm wire brushes, thus, had twice the impaction area of the 1-mm wire brushes. At brush speeds below 3000 RPM, significantly higher separation efficiencies were obtained with the 2-mm wire brushes at slightly more horsepower. Essentially identical performance was observed at 3000 RPM with separation efficiencies of 94-95% at nearly 7 HP. Figure 43 with half as many wires (only two of the full complement brushes instead of four as in Fig. 42) shows the same effect to a lesser extent.

While the 1-mm wires appear to be more efficient than the 2-mm wires on a constant impaction area basis, as one would expect from impaction theory, consideration of the problem of wire erosion and ease of maintenance favors the use of heavier wires. If the same total number of wires is used as the comparison criterion, no difference is observed at 3000 RPM, and somewhat higher separation efficiencies are obtained with the 2-mm wire brushes at lower brush speeds. Therefore, in the final series of tests with narrow size fractions of classified tests dusts, the decision was made to use the 2-mm wire brushes with the complete complement of four brushes, 48 wires/row, and 12 rows/brush.

6. Particle Size Effects

The relationship between separation efficiency and dust particle size was evaluated at 8000 CFM with the full complement of 2304 wires on four brushes. The wire size selected for this last series of tests was 2 mm, based on the reasons stated in the previous section. Five different test dusts were utilized whose size distributions were shown previously in Fig. 8 (p. 17). One of the test dusts was, of course, the Ansul +50B sodium bicarbonate as supplied which was used for the majority of the tests itemized in Table 1 (pp. 12-16). The Ansul +50B was also classified into three smaller size fractions through the use of a Bahco classifier. This technique permitted the size range of from 15-μm to 46-μm to be covered with the sodium bicarbonate. Ball-milled anthracite coal with a mass median diameter of 2.7-μm was used to cover the small particle region where separation efficiency falls off rapidly. The tests with sodium bicarbonate were assessed as usual by chemical titration of the filter samples. The tests with coal dust were assessed by gravimetric analysis of the filter samples.

Blank tests were run to determine more accurately the true operating separation efficiency since transient conditions during the start-up and shut-down periods of a test contributed a small amount of dust to the downstream sampler which would not otherwise reach the sampler during continuous operation. Even without the correction for the blank in these tests, efficiencies instead of approaching 100% for the classified sodium bicarbonate were on the order of 95%. In an on-board helicopter engine air-particle separator, provision can be made for rotating the brush at speed during these transient periods. This was not possible during the tests due to the danger of excessive brush speeds at conditions of no load or reduced load when the inlet air volume is low. A speed limiting governor will correct this situation and provide additional particle protection to the gas turbine.

It is evident from Fig. 44 that, as expected, particle size has no measurable effect on horsepower requirements. At 8000 CFM and 3000 RPM, the brush horsepower required 7 HP, is a function of the air volume and RPM conditions alone and the extremely low increment of mass contributed by the dust compared to the mass of the air is insufficient to make a measurable increase in the horsepower requirements.

In the particle size region of 15-35 μm, the particle separation efficiency is essentially 100%. In the region between 15-μm and 2.7-μm, the separation efficiency falls off rapidly, but an efficiency of 66% at 2.7-μm was surprisingly high for such small particles.

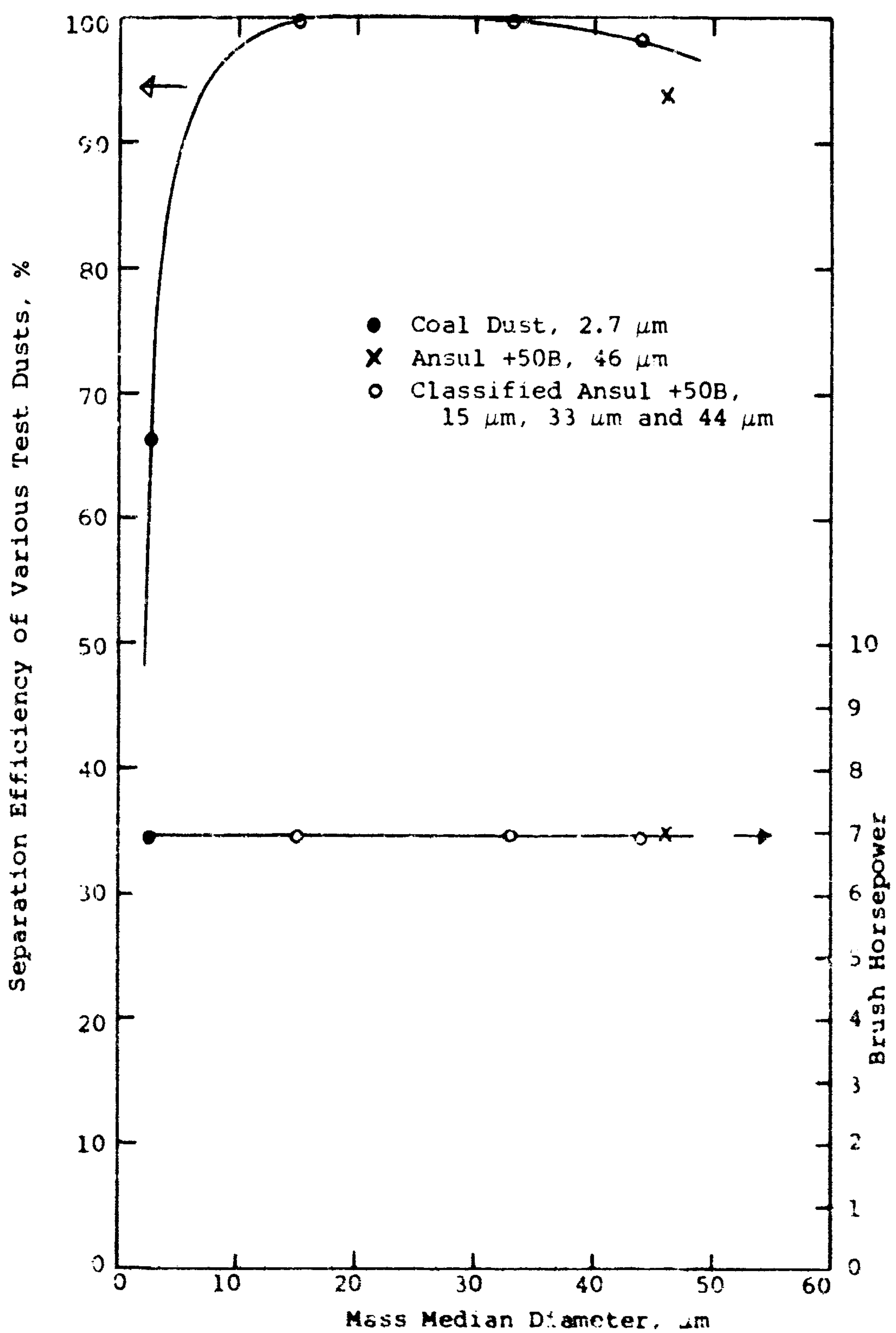

Fig. 44: Separation Efficiency and Horsepower vs. Test Dust Particle Size at 8000 CFM with Near Exhaust and 2 mm Wires (4 brushes, 48 wires/row, 12 rows/brush) at 3000 RPM

Above 35-μm, the separation efficiency appears to drop away somewhat from 100%. Perhaps this is due to the tendency of the brush separator to pulverize some of the larger, more friable particles of sodium bicarbonate on impact with the wires. This may be less of a problem with harder materials, such as sand. A simple solution to this tendency, if it appears to be a serious problem in field use, is to precede the brush separator with an inertial separator designed to remove most particles above 50-μm in size. Or, the brush separator can be staged, with the first brush element containing larger diameter wires or elements to better withstand the abrasive action of these larger particles. Succeeding brushes would then have progressively finer wires to remove smaller particles. It is apparent that the separator efficiency in the below 15-μm region can be improved if the 2-mm wire brushes are followed up with a polishing action by finer wire brushes, which would not be exposed to the more abrasive environment of the preceding more robust brushes.

IV. SUMMARY & CONCLUSIONS

A. Residence Time (Exhaust Position)

The highest efficiencies were obtained with the near exhaust position when the wire brush speeds exceeded 2400 RPM. It is believed that turbulent mixing downstream of the brushes is the region ahead of the exhaust annulus defeated any improvement in separation efficiency that might have been possible with the longer residence time associated with the far exhaust position. Therefore, any additional separation length must be filled with additional brushes to take advantage of a longer residence time.

B. Centrifugal Effects

Centrifugal effects for Ansul + 50 B dust have been found to be an important separation mechanism, although impaction effects significantly enhance separation at brush speeds above 2400 RPM. In comparable tests with flat blades versus 1-mm wires, the wire brushes required 15% less horsepower at 3,000 RPM and 8,000 CFM to achieve a 95% separation efficiency compared to 86% for the flat-blade brushes. It was not possible to completely separate centrifugal and impaction effects in the tests conducted with Ansul + 50 dust because of the presence of impaction scavenging of large particles even with the flat blades. A smaller particle test dust would show even more differences in separation for the wire brushes compared to the flat blades.

C. Axial and Radial Spacing Between Wires

In the tests with the 1-mm wire brushes at a constant total projected wire width of 1152-mm, the differences in efficiency and horsepower for axial versus radial spacing between wires are slight and are not significant.

In the 2-mm wire brushes the method of wire spacing becomes important. As the brush RPM increases and separation efficiency rises, the four-brush configuration becomes increasingly superior to the corresponding two-brush configuration using the same total number of wires. The significance of the results of the wire spacing tests is that 2-mm wires added to a configuration in the axial direction are more effective than wires added in the radial direction.

D. Impaction Area

At 3,000 RPM and 8,000 CFM, when the number of brushes was doubled, the amount of dust which was not removed by the separator was reduced by one-half. With 2-mm wire brushes at 2,400 RPM, the increase in impaction area in going from two

brushes to four brushes is beneficial only above 3,000 CFM. The number of brushes required for a given application will depend on the air volume requirements among other factors. While two brushes may be adequate for separation of Ansul +50B dust at 3,000 CFM, at 8,000 CFM half of the dust which penetrated two brushes was removed by adding two more brushes.

E. Wire Size Effects

On a constant impaction area basis, the 1-mm wire brushes tended to be more effective than the 2-mm wire brushes in the two-brush configuration. No significant difference was noted, however, in the four-brush configuration. When the total number of wires was kept constant (2,304) the 2-mm wire brushes were more effective at brush speeds below 3,000 RPM. At 3,000 RPM the efficiency curves then appeared to cross over, suggesting that above 3,000 RPM the 1-mm wire brushes would surpass the effectiveness of the 2-mm wire brushes with the same total number of wires. Since the smallest particles are undoubtedly removed more effectively at the higher brush speeds, the crossing of the curves above 3,000 RPM further suggests that the smaller the particle to be removed, the smaller the wire element needed to remove that particle with the same effectiveness.

While the 1-mm wires appear to be more efficient than the 2-mm wires on a constant impaction area basis, consideration of wire erosion and ease of maintenance favors the use of the heavier wires.

F. Particle Size Effects

Separation efficiencies at 8,000 CFM and 3,000 RPM approached 100% for size-classified test dusts in the 15-35 μm size range. At 2.7-μm the separation efficiency had fallen to a respectable 66%. Above 35-μm the separation efficiency on the sodium bicarbonate test dust appears to drop away somewhat from 100%, perhaps due to some large particle size reduction by impact with the brush wires.

G. Power Consumption

Only 7 HP was required to rotate the brush shaft at 3,000 RPM for 8,000 CFM and at a pressure drop of only 4-in of water, the conditions used in evaluating particle size effects with the full complement of 2-mm wire brushes.

V. RECORDS AND PERSONNEL

Data are recorded in IITRI Logbook C19929 and the test data sheets are entered in the Project Data Book C6206. Most of the tests were conducted by Dennis Krebs and Erdmann Luebcke. Edmund Swider and William Kiscellus redesigned the brush separator. Administrative supervision has been under the direction of Meryl Jackson and John Stockham.

VI. FUTURE WORK

Now that the experimental parametric investigation of the design and operating variables of the brush separator has been completed, it is recommended that a flight model compatible with a specific turbine engine be designed and built. A more thorough analysis of the voluminous data obtained to date may permit a modification of Socle's design parameters to be applied to the design of such a flight model separator. Time limitations on the current program did not permit such an analysis to be made, but such a combination of theory and experimental results should allow the calculation of design requirements based on theoretical-empirical relationships.

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5. AUTHOR(S) (Last name, first name, initial)

Werle, Donald K.

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13. ABSTRACT

The rotating brush aerosol separator developed previously was redesigned and modified to permit a parametric investigation of the design and operational variables. While centrifugal effects were found to be important, impaction effects significantly enhance separation at brush speeds above 2,400 RPM. The highest efficiencies were obtained when the wire brush speeds exceeded 2,400 RPM. While the 1-mm wires appear to be more efficient than the 2-mm wires on a constant impaction area basis, consideration of wire erosion and ease of maintenance favors the use of the heavier wires. Separation efficiencies at 8,000 CFM and 3,000 RPM approached 100% for size classified test dusts in the 15- to 35-μm size range. At 2.7-μm, the separation efficiency fallen to a respectable 66%. Above 35 μm, the separation efficiency on the sodium bicarbonate test dust appears to drop away somewhat from 100%, perhaps due to some large-particle size reduction by impact with the brush wires. Only 7 HP was required to rotate the brush shaft at 3,000 RPM for 8,000 CFM and at a pressure drop of only 4-in. of water.

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Air cleaner						
Engine Air particle separator						
Turbine engine protection						

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Appendix A

ENGINEERING DRAWINGS OF THE MODIFIED BRUSH SEPARATOR AND SEPARATOR COMPONENTS

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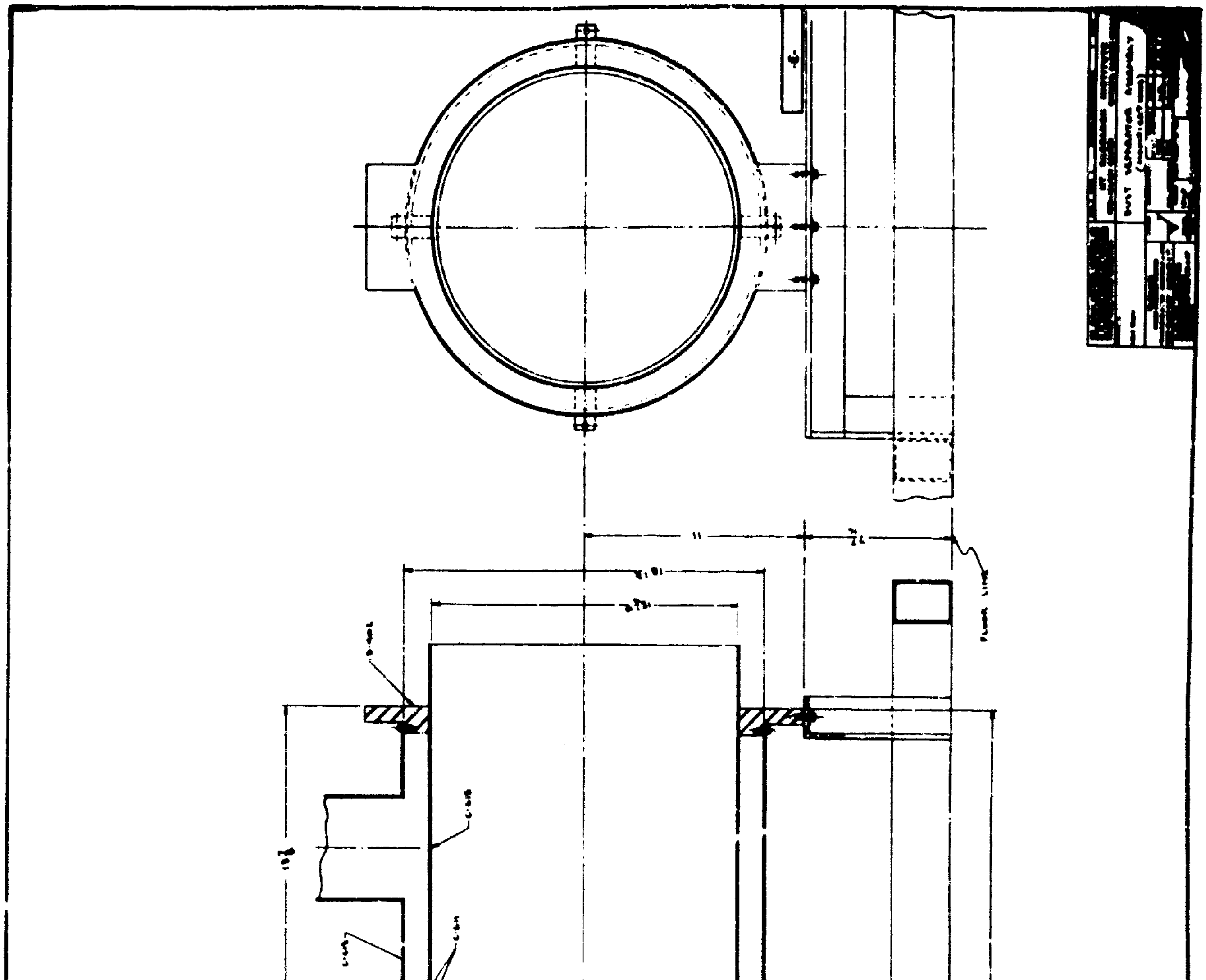
REVISION

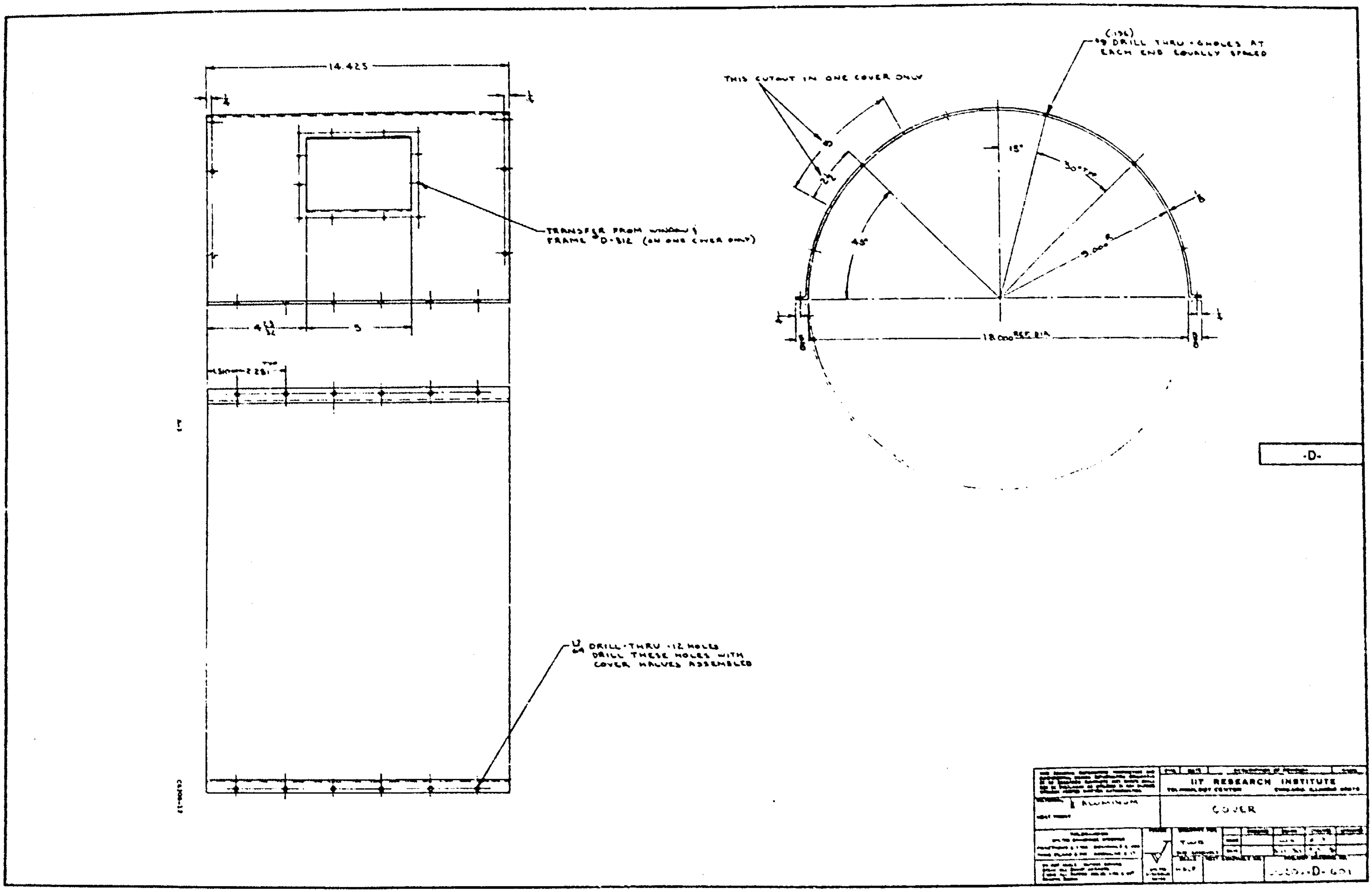
SHEET
OF

PROJECT No.	PARTS LIST FOR		
C-6206	DUST SEPARATOR - MODIFICATIONS		

DRAWING No.	PART NAME	TOTAL QUANTITY	DESCRIPTION & SPECIFICATION
E-600	ASSEMBLY		
D-601	COVER	TWO	USE WINDOW FROM D-312
B-602	END PLATE	TWO	
C-603	BRUSH ASSEMBLY (STYLE 1)	96	
C-604	BRUSH ASSEMBLY (STYLE 2)	96	
C-605	BRUSH ASSEMBLY (STYLE 3)	48	
B-606	HUB	FOUR	
B-607	RETAINER RING	EIGHT	
C-608	SHAFT	ONE	
A-609	SPACER	THREE	
A-610	BRG SPACER	ONE	
C-611	RING	TWO	
C-612	DUST COLLECTING TUBE (REMOVEABLE)	ONE	MAKE FROM OLD PART # D-403
C-613	DUST COLLECTING TUBE (STATIONARY)	ONE	
C-614	EXHAUST TUBE (REMOVEABLE)	ONE	MAKE FROM OLD PART # D-401
C-615	EXHAUST TUBE (STATIONARY)	ONE	
	NEW	HARD	WARE
619	SCREW	48	~~FLAT HD~~ SCREW - 10-32 x $\frac{1}{2}$ LG S.S.
620	SCREW	48	SOC. HD. CAP SCREW - 10-32 x $\frac{3}{8}$ LG S.S.
621	SCREW		SOC. HD. CAP SCREW 10-32 x 1 LG STEEL
622	WASHER		10-32 WASHER
623	NUT	4	10-32 NUTS
624	KEY	ONE	$\frac{3}{16} \times \frac{3}{16} \times 12\frac{1}{8}$ LG
307	BEARING	TWO	"NICE" BRG CAT. No 1630 DC

C6206-12

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45°
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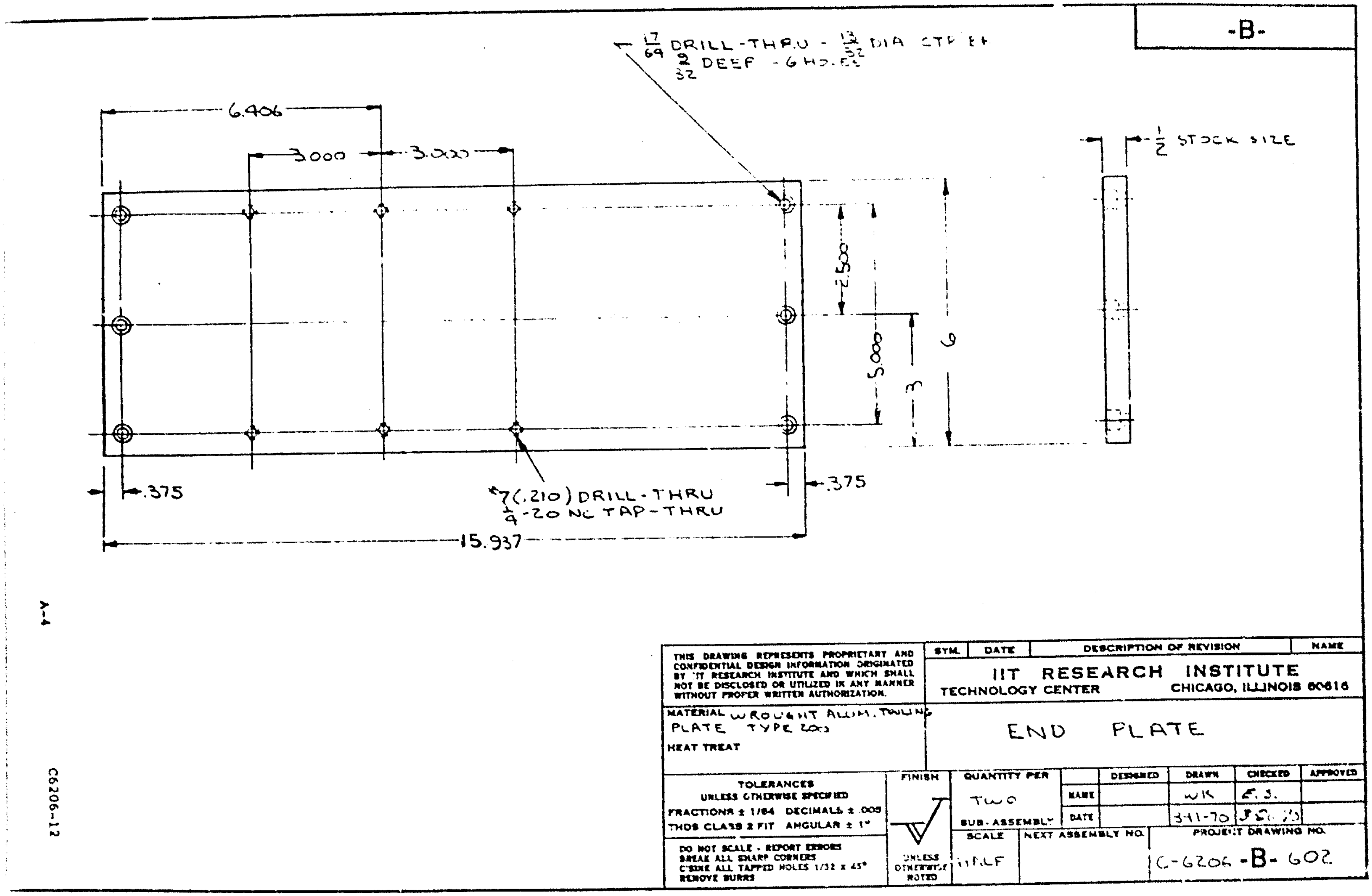
IIT RESEARCH INSTITUTE
ALUMINUM
COVER

C6306-17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17/64 DRILL-THRU - 13/32 DIA CTR BR
2/32 DEEP - 6 HOLES
6.406
3000
3.000
1/2 STOCK SIZE
2.500
5.000
3
6
.375
.375
*7 (.210) DRILL-THRU
1/4-20 NC TAP-THRU
15.937
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HEAT TREAT
END PLATE
TOLERANCES
UNLESS OTHERWISE SPECIFIED
FRACTIONS ± 1/64 DECIMALS ± .005
THDS CLASS 2 FIT ANGULAR ± 1°
DO NOT SCALE - REPORT ERRORS
BREAK ALL SHARP CORNERS
C'SINK ALL TAPPED HOLES 1/32 x 45°
REMOVE BURRS
FINISH
UNLESS OTHERWISE NOTED
QUANTITY PER
TWO
SUB-ASSEMBLY
SCALE
HALF
NEXT ASSEMBLY NO.
DESIGNED DRAWN CHECKED APPROVED
NAME WK E.S.
DATE 3-11-70
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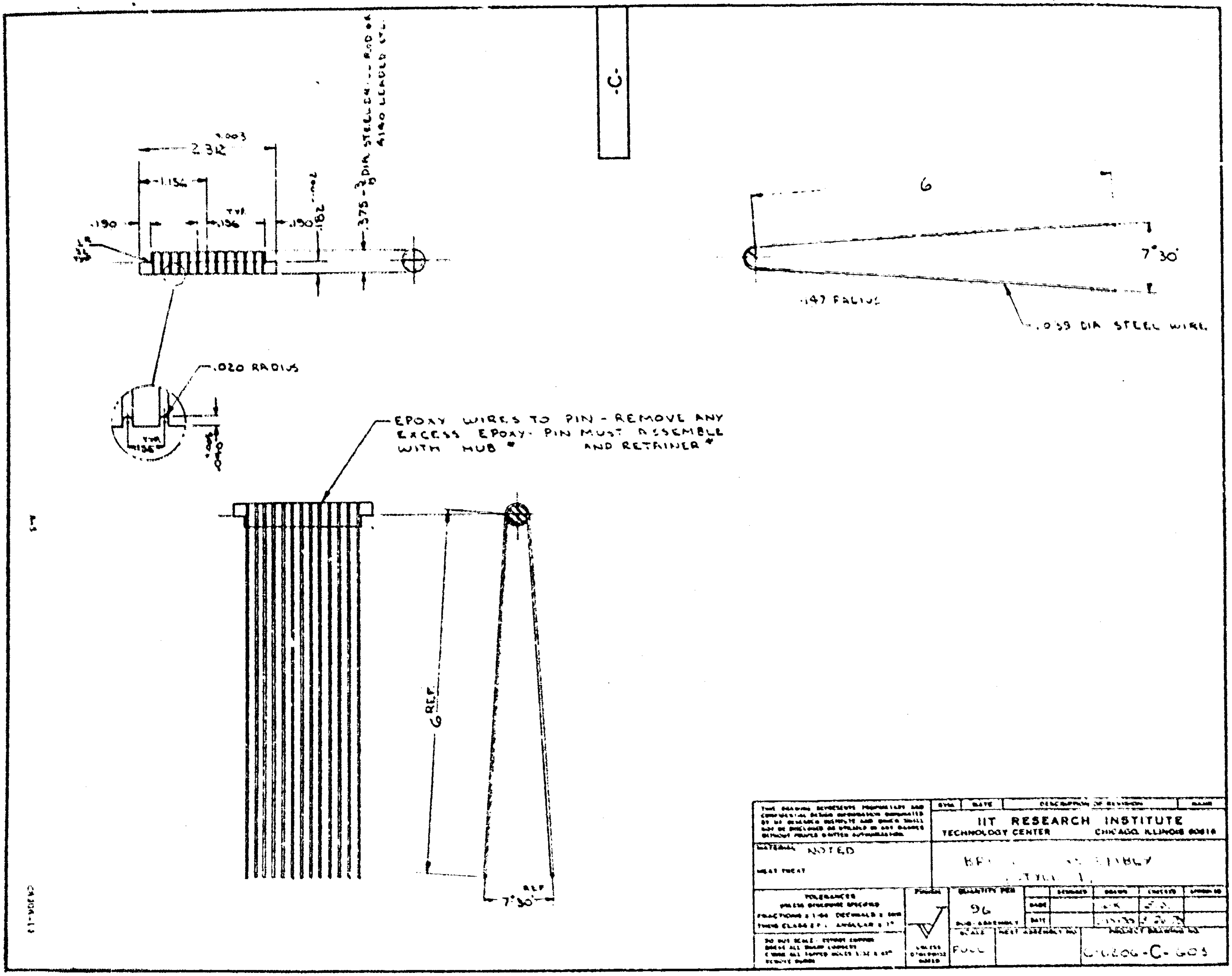

-C-
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.156 TYP
.190
.182 ±.002
.375 - 3/8 DIA STEEL ... ROD OR 4140 LEADED STL
.020 RADIUS
.156 TYP
.040 ±.005
6
7°30'
.147 RADIUS
.039 DIA STEEL WIRE
EPOXY WIRES TO PIN - REMOVE ANY EXCESS EPOXY. PIN MUST ASSEMBLE WITH HUB # AND RETAINER #
6 REF
7°30' REF
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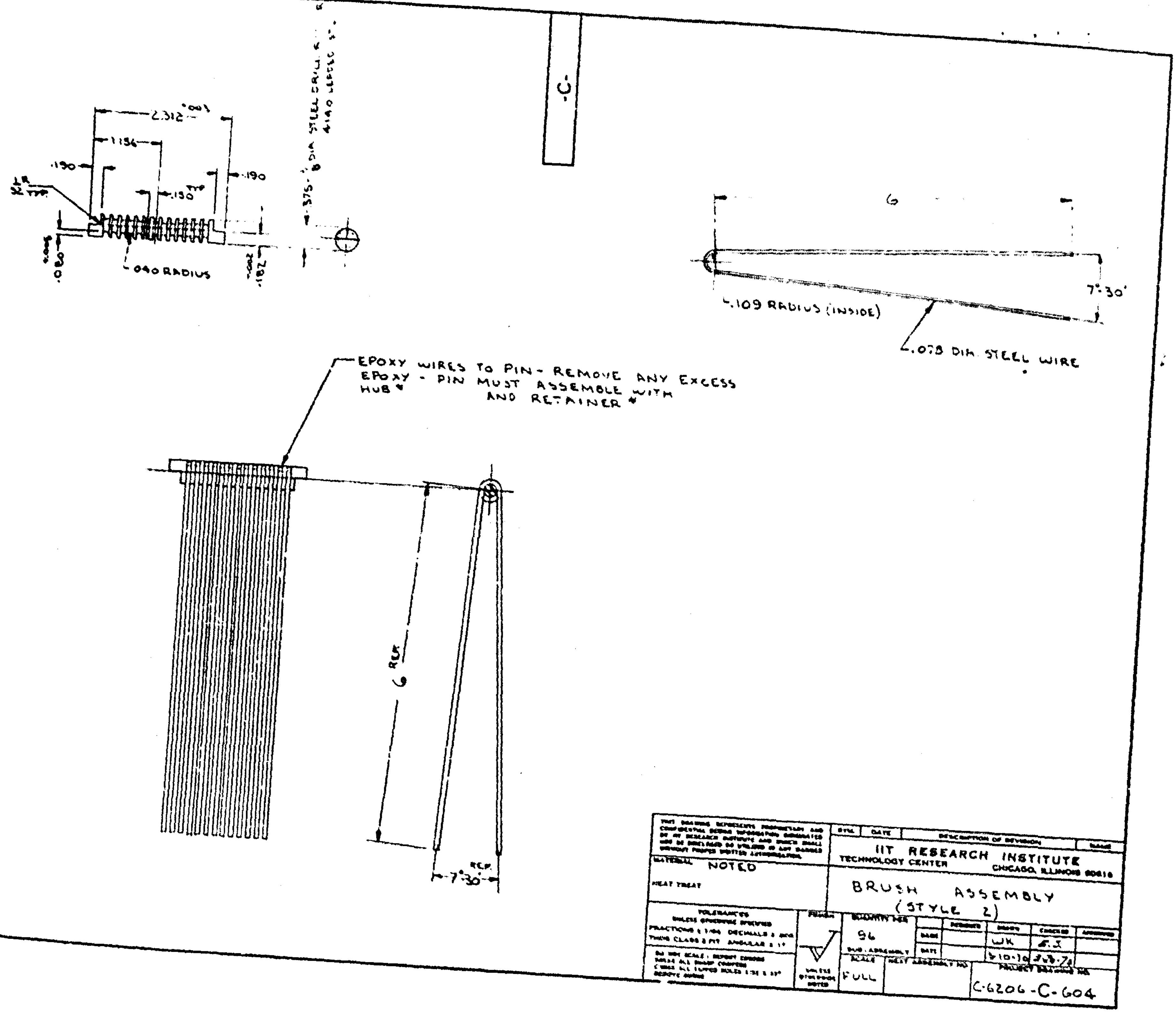

-C-
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.375 - 1/8 DIA STEEL DRILL ROD 4140 LEFSEC
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7°30'
.109 RADIUS (INSIDE)
.078 DIA STEEL WIRE
EPOXY WIRES TO PIN - REMOVE ANY EXCESS EPOXY - PIN MUST ASSEMBLE WITH HUB # AND RETAINER #
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7°30' REF.
MATERIAL NOTED
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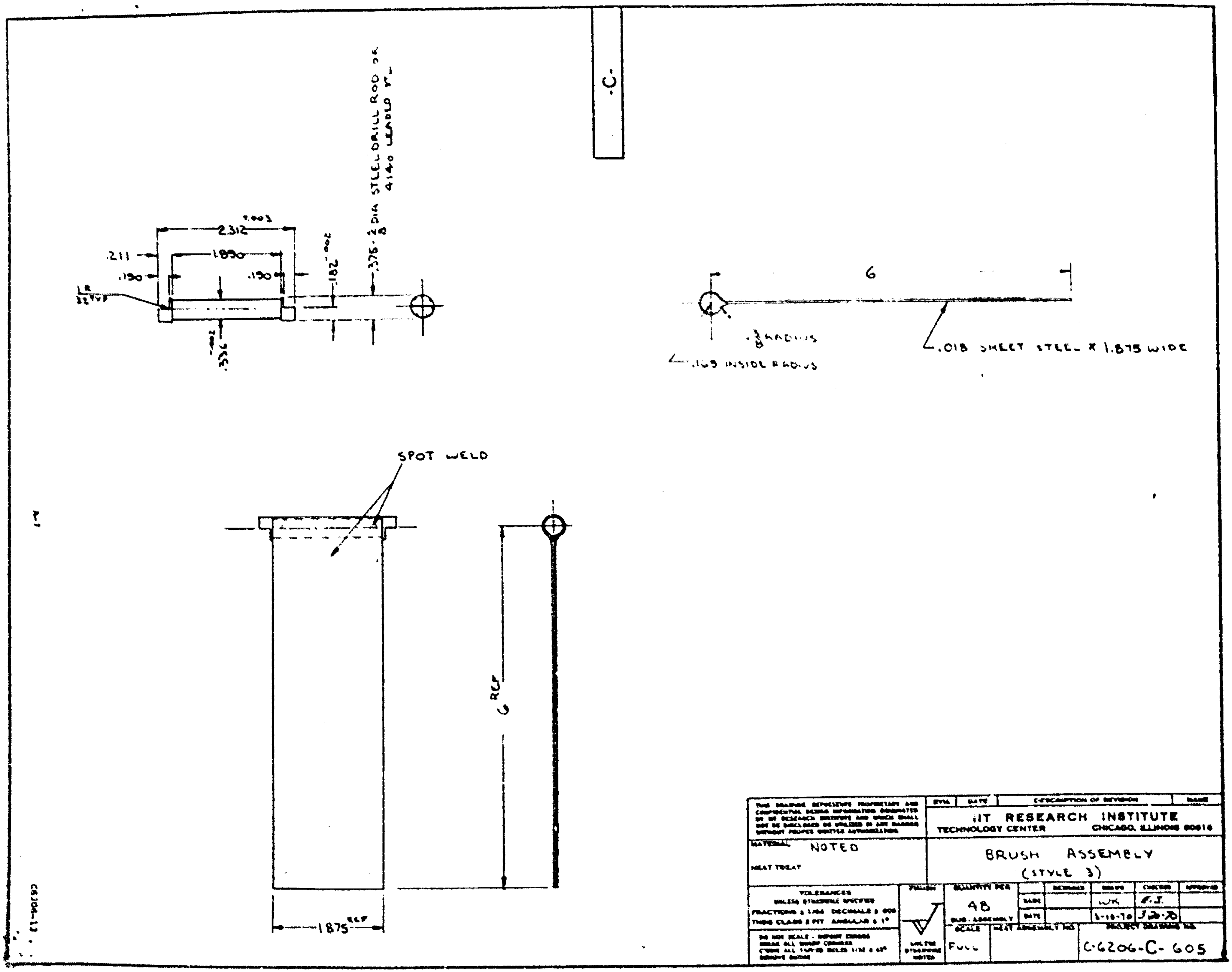
BRUSH ASSEMBLY (STYLE 2)
96
JK
FULL
C-6206-C-604


-C-
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.190
.190
1/8 / 32 TYP
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.375 - 3/8 DIA STEEL DRILL ROD OR 4140 LEADED ST.
.336 ±.002
6
3/8 RADIUS
.165 INSIDE RADIUS
.018 SHEET STEEL X 1.875 WIDE
SPOT WELD
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REMOVE BURRS
FINISH
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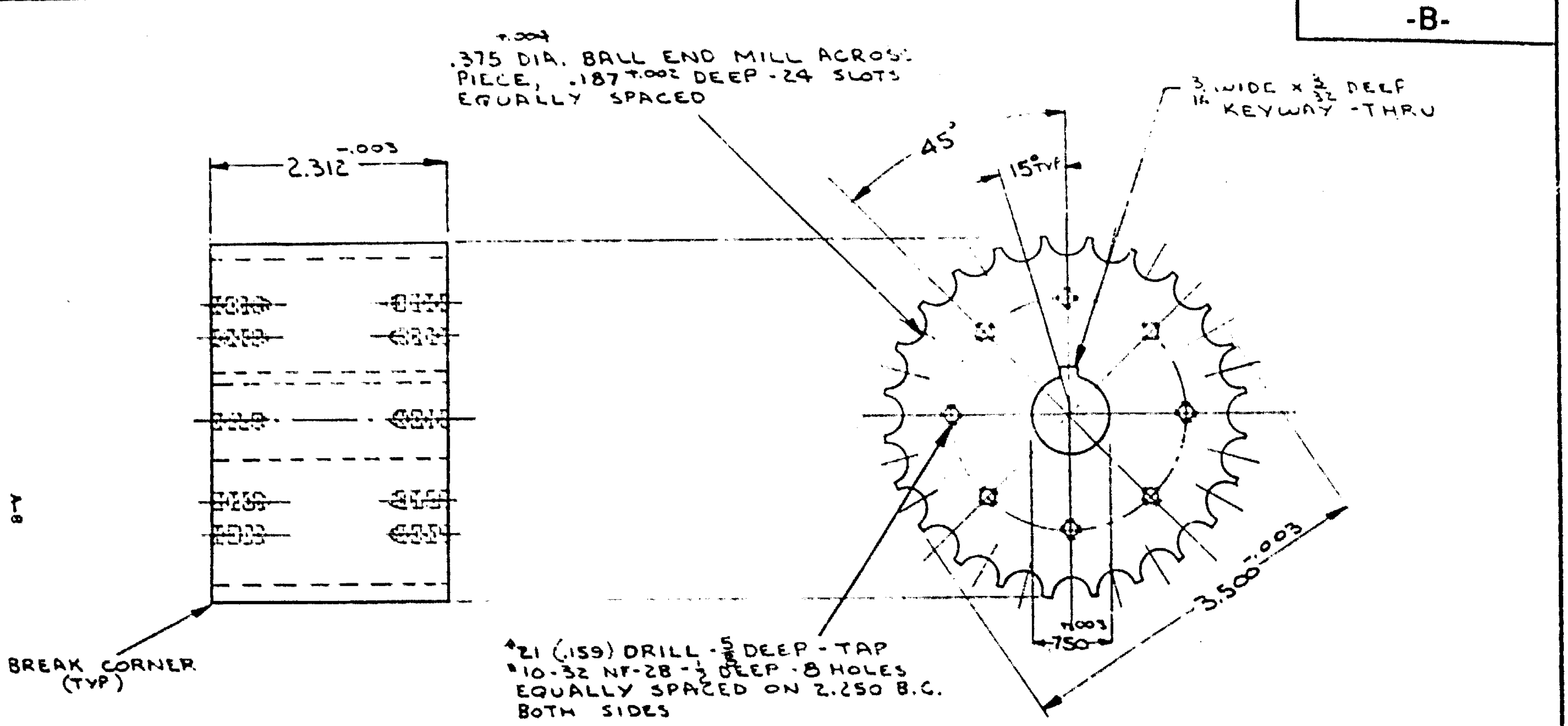
BRUSH ASSEMBLY
(STYLE 3)
DESIGNED DRAWN CHECKED APPROVED
NAME WK F.J.
DATE 3-18-70 3-20-70
PROJECT DRAWING NO.
C-6206-C-605

C6206-13



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SYM.	DATE	DESCRIPTION OF REVISION	NAME

IIT RESEARCH INSTITUTE
TECHNOLOGY CENTER — CHICAGO, ILLINOIS 60616

MATERIAL 2024-T4 ALUMINUM

HEAT TREAT

HUB

TOLERANCES
UNLESS OTHERWISE SPECIFIED
FRACTIONS ± 1/64 DECIMALS ± .005
THDS CLASS 2 FIT ANGULAR ± 1°

DO NOT SCALE - REPORT ERRORS
BREAK ALL SHARP CORNERS
C'SINK ALL TAPPED HOLES 1/32 x 45°
REMOVE BURRS

FINISH 63 UNLESS OTHERWISE NOTED

QUANTITY PER SUB-ASSEMBLY: FOUR

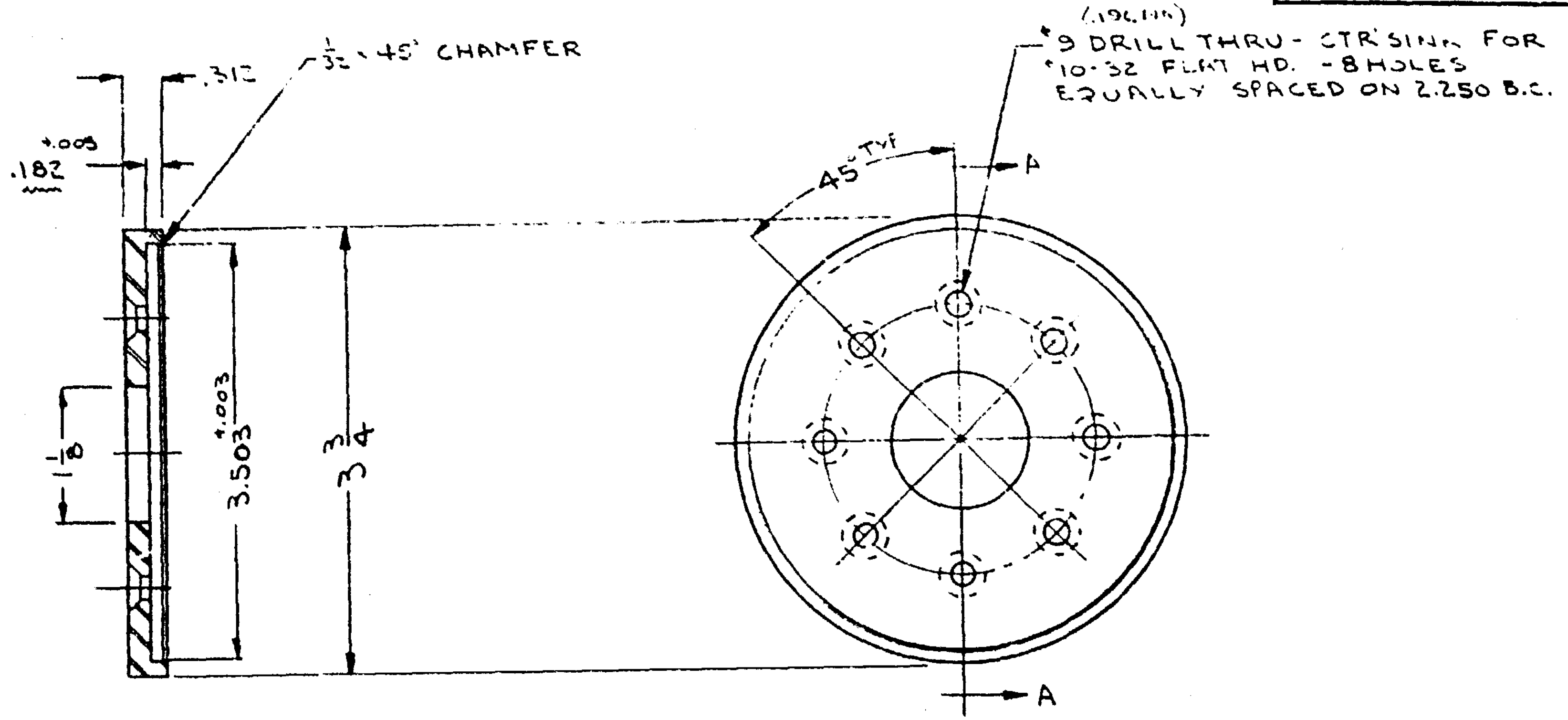
SCALE: FULL

NEXT ASSEMBLY NO.

	DESIGNED	DRAWN	CHECKED	APPROVED
NAME		WK	F.S.	
DATE		3-5-70	3-20-70	

PROJECT DRAWING NO. C-6206-B-606

-B-



SECTION A-A

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SYM.	DATE	DESCRIPTION OF REVISION	NAME

IIT RESEARCH INSTITUTE
TECHNOLOGY CENTER CHICAGO, ILLINOIS 60616

MATERIAL STEEL

HEAT TREAT

RETAINER RING

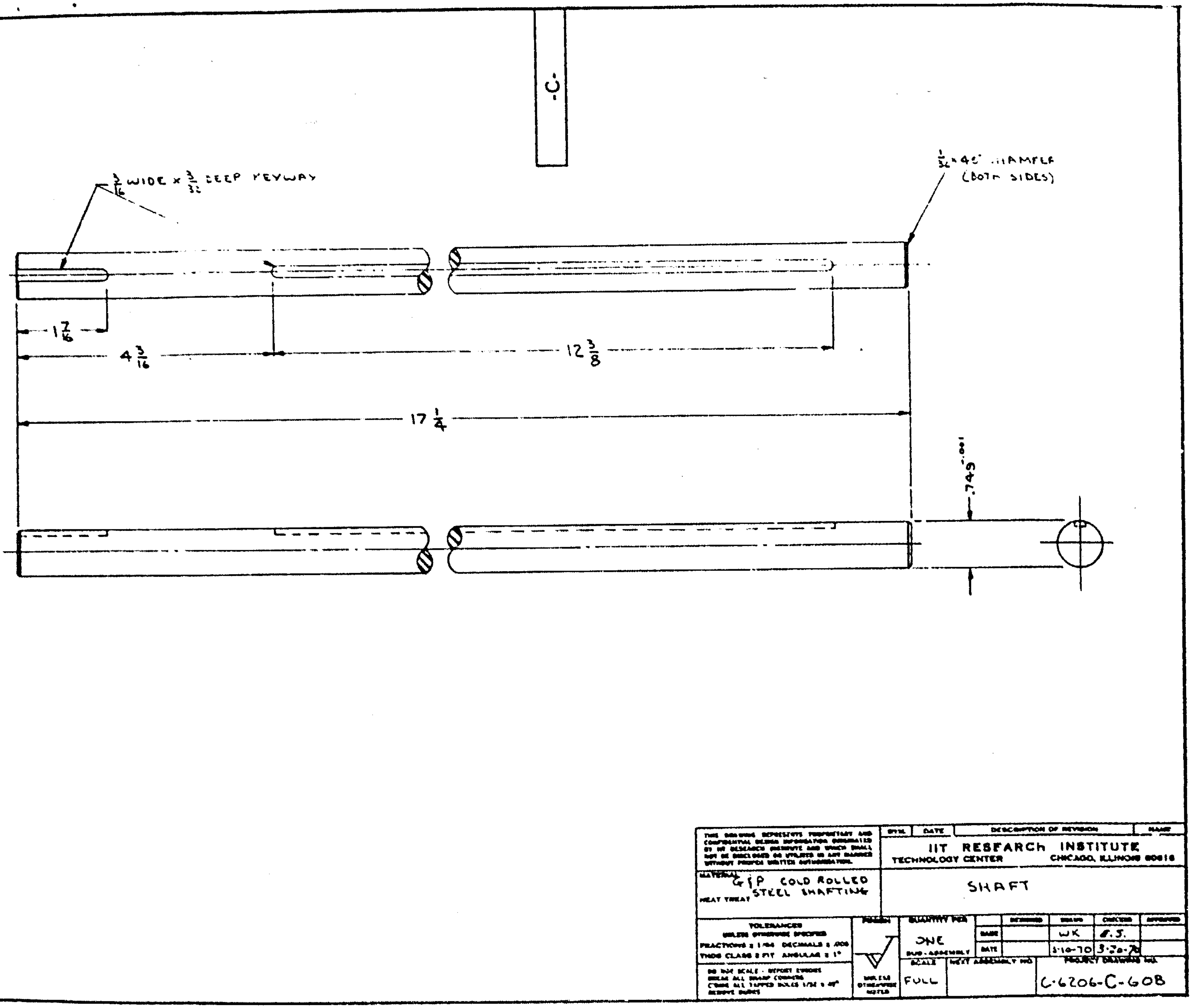
TOLERANCES
UNLESS OTHERWISE SPECIFIED
FRACTIONS ± 1/64 DECIMALS ± .005
THDS CLASS 2 FIT ANGULAR ± 1°

DO NOT SCALE - REPORT ERRORS
BREAK ALL SHARP CORNERS
C'SINK ALL TAPPED HOLES 1/32 x 45°
REMOVE BURRS

FINISH 125 UNLESS OTHERWISE NOTED

QUANTITY PER		DESIGNED	DRAWN	CHECKED	APPROVED
EIGHT	NAME		WK	[illegible]	
SUB-ASSEMBLY	DATE		3-9-70	3-20-70	

SCALE	NEXT ASSEMBLY NO.	PROJECT DRAWING NO.
FULL		C-6206-B-607



-C-
3/16 WIDE x 3/32 DEEP KEYWAY
1/32 x 45° CHAMFER (BOTH SIDES)
1 7/16
4 3/16
12 3/8
17 1/4
.749 -.001
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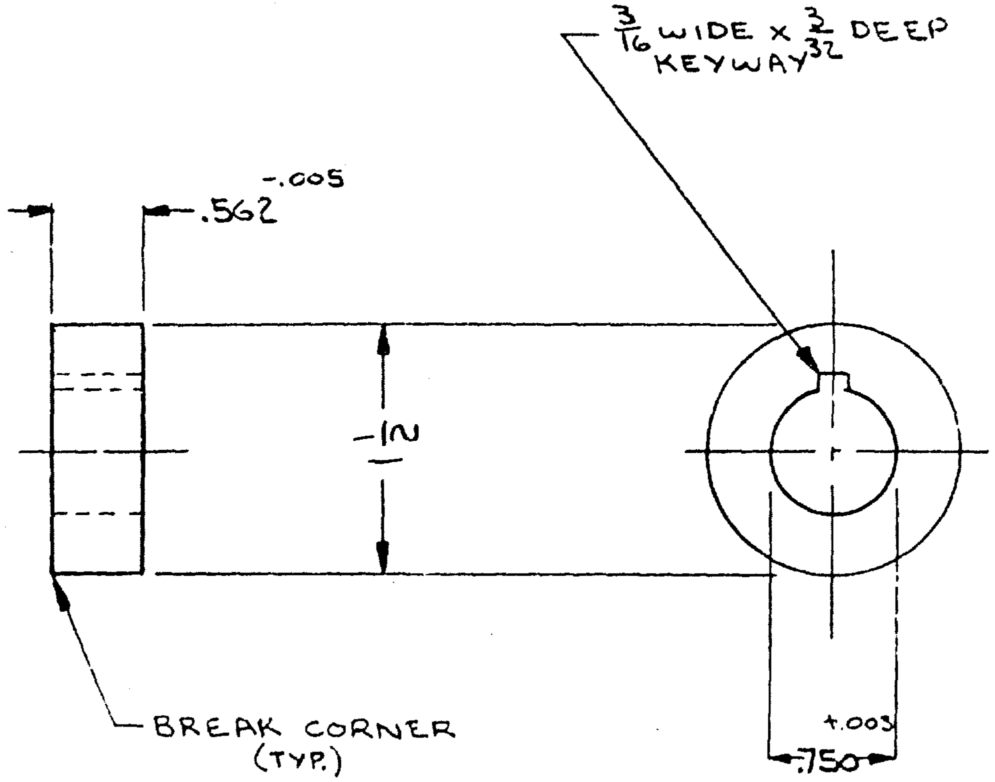
MATERIAL G.F.P. COLD ROLLED STEEL SHAFTING
HEAT TREAT
TOLERANCES UNLESS OTHERWISE SPECIFIED
FRACTIONS ± 1/64 DECIMALS ± .005
THDS CLASS 2 FIT ANGULAR ± 1°
DO NOT SCALE · REPORT ERRORS
BREAK ALL SHARP CORNERS
C'SINK ALL TAPPED HOLES 1/32 x 45°
REMOVE BURRS
FINISH
UNLESS OTHERWISE NOTED
QUANTITY PER
ONE
SUB-ASSEMBLY
SCALE
FULL
NEXT ASSEMBLY NO.
SYM.
DATE
DESCRIPTION OF REVISION
NAME
IIT RESEARCH INSTITUTE
TECHNOLOGY CENTER
CHICAGO, ILLINOIS 60616
SHAFT
DESIGNED
DRAWN
CHECKED
APPROVED
NAME
WK
E.S.
DATE
3-10-70
3-20-70
PROJECT DRAWING NO.
C-6206-C-608

C6206-12

-A-



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SYM.	DATE	DESCRIPTION OF REVISION	NAME

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TECHNOLOGY CENTER CHICAGO, ILLINOIS 60616

MATERIAL BRASS ROD

HEAT TREAT

SPACER

TOLERANCES UNLESS OTHERWISE SPECIFIED
FRACTIONS ± 1/64 DECIMALS ± .005
THDS CLASS 2 FIT ANGULAR ± 1°

DO NOT SCALE - REPORT ERRORS
BREAK ALL SHARP CORNERS
C'SINK ALL TAPPED HOLES 1/32 x 45°
REMOVE BURRS

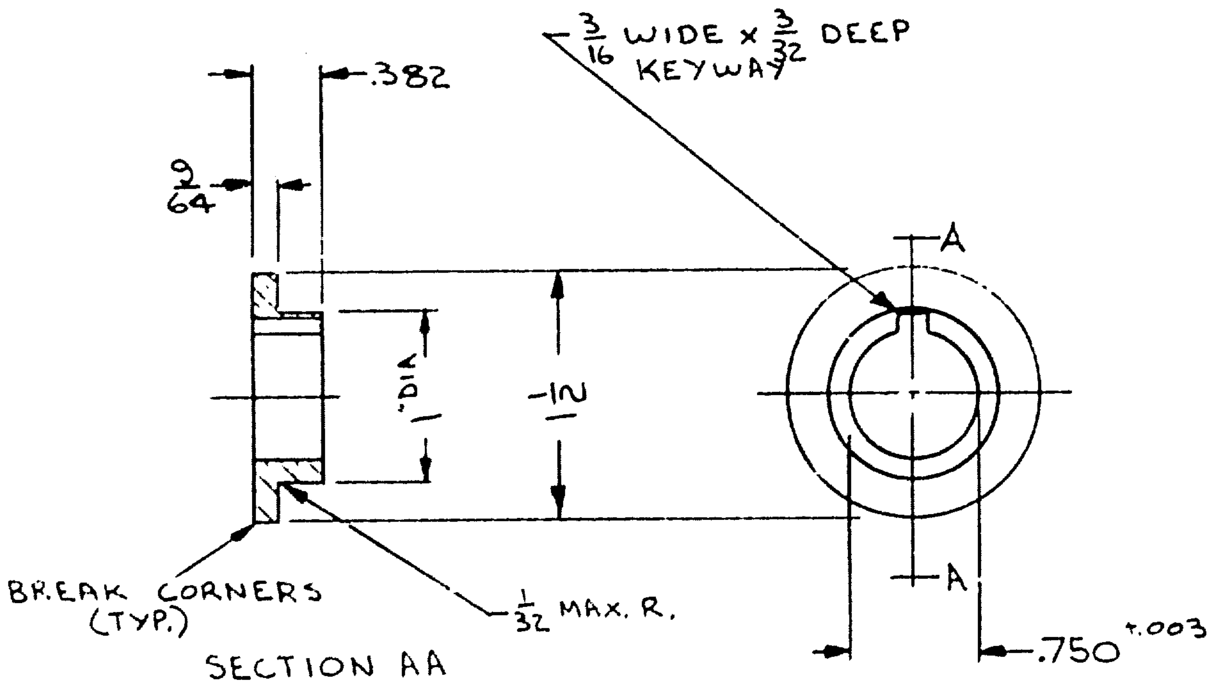
FINISH 125 UNLESS OTHERWISE NOTED

QUANTITY PER THREE
SUB-ASSEMBLY

	DESIGNED	DRAWN	CHECKED	APPROVED
NAME		WK	E.S.	
DATE		3-9-70	3-20-70	

SCALE	NEXT ASSEMBLY NO.	PROJECT DRAWING NO.
FULL		C-6206-A-609

-A-



SYM.	DATE	DESCRIPTION OF REVISION	NAME

IIT RESEARCH INSTITUTE
TECHNOLOGY CENTER CHICAGO, ILLINOIS 60616

MATERIAL BRASS ROD

HEAT TREAT

BEARING SPACER

TOLERANCES UNLESS OTHERWISE SPECIFIED
FRACTIONS ± 1/64 DECIMALS ± .005
THDS CLASS 2 FIT ANGULAR ± 1°

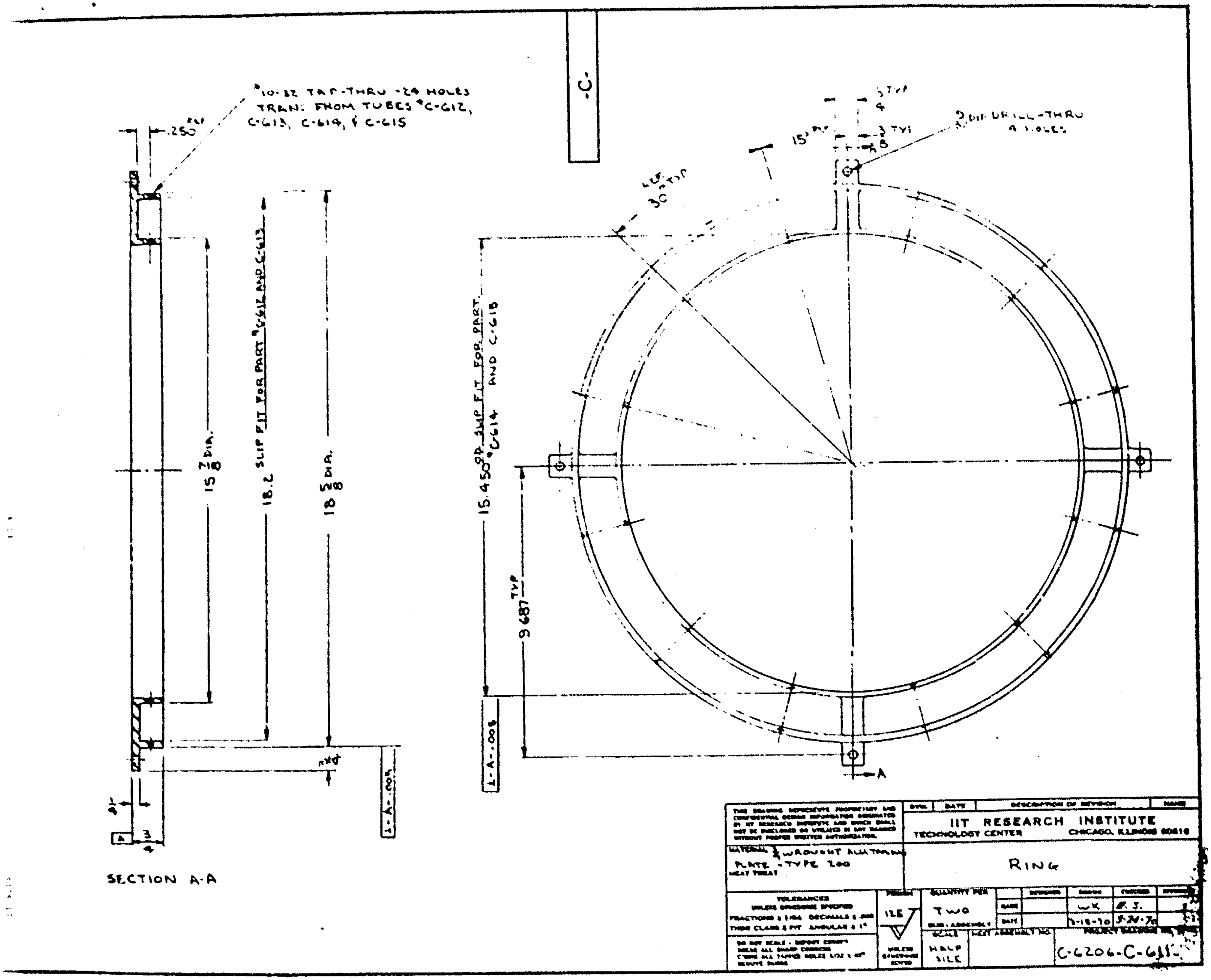
FINISH 125 UNLESS OTHERWISE NOTED

QUANTITY PER ONE SUB-ASSEMBLY

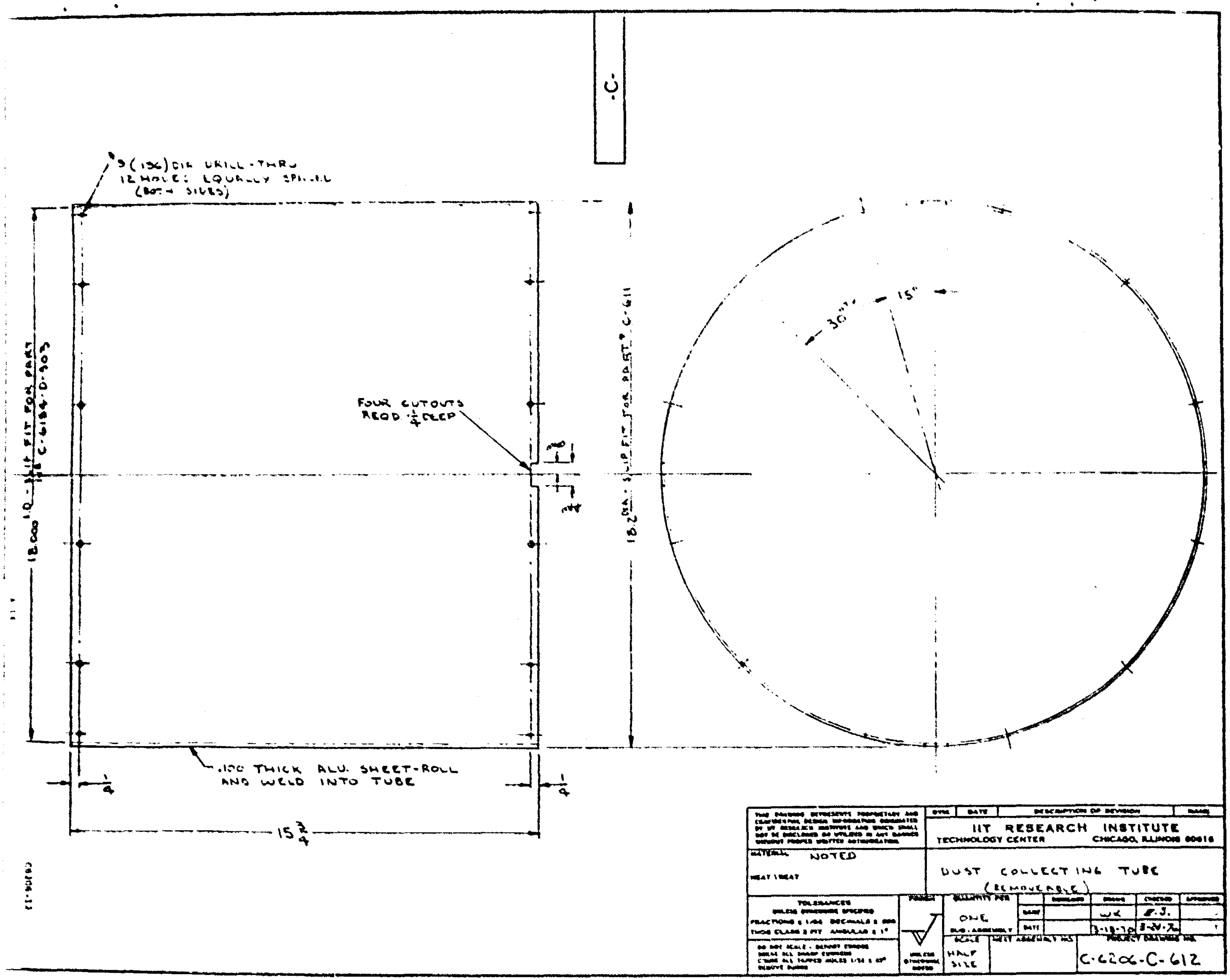
	DESIGNED	DRAWN	CHECKED	APPROVED
NAME		WK	E.S.	
DATE		3-9-70	3-20-70	

DO NOT SCALE - REPORT ERRORS
BREAK ALL SHARP CORNERS
C'SINK ALL TAPPED HOLES 1/32 x 45°
REMOVE BURRS

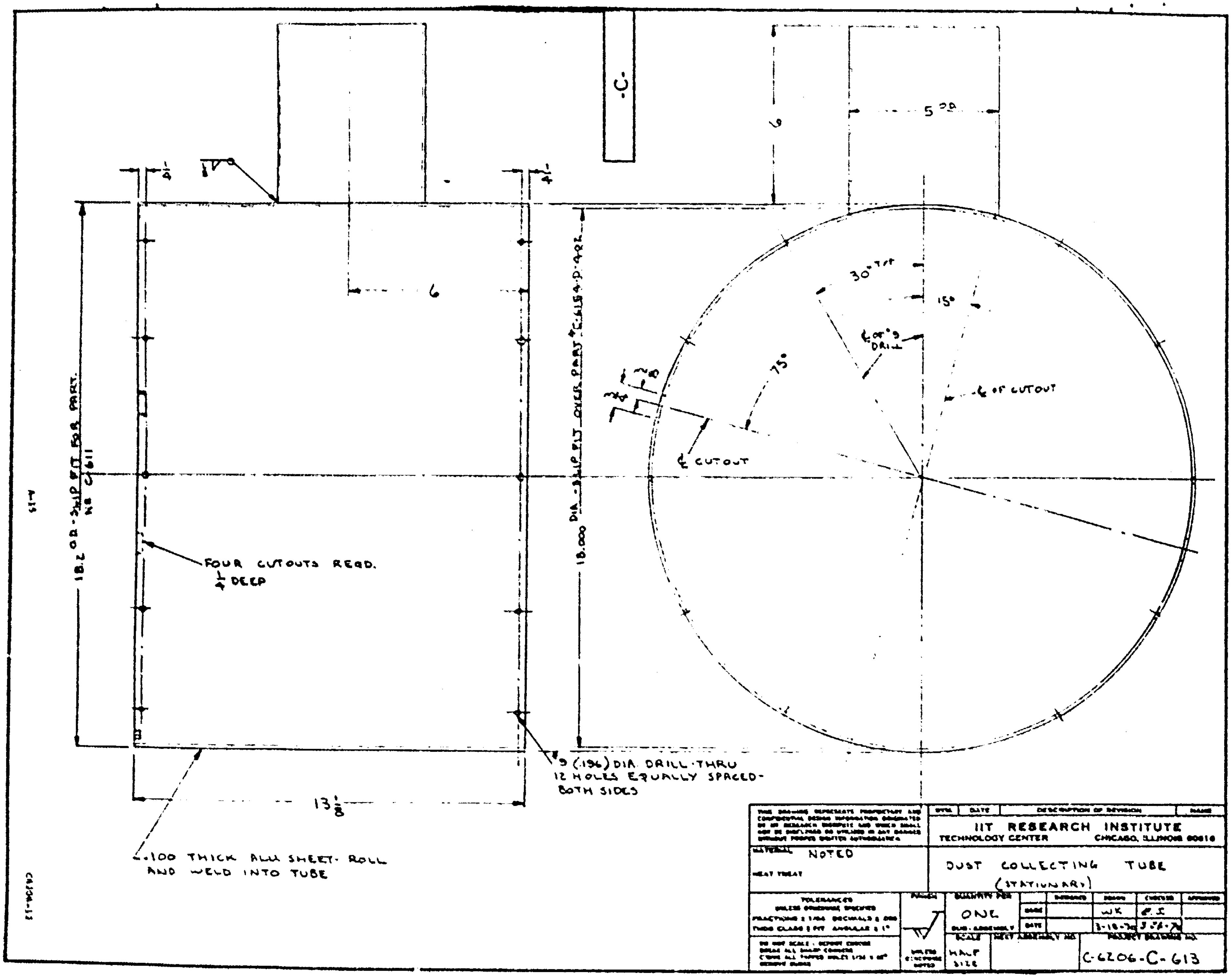
SCALE	NEXT ASSEMBLY NO.	PROJECT DRAWING NO.
FULL		C-6206-A-610



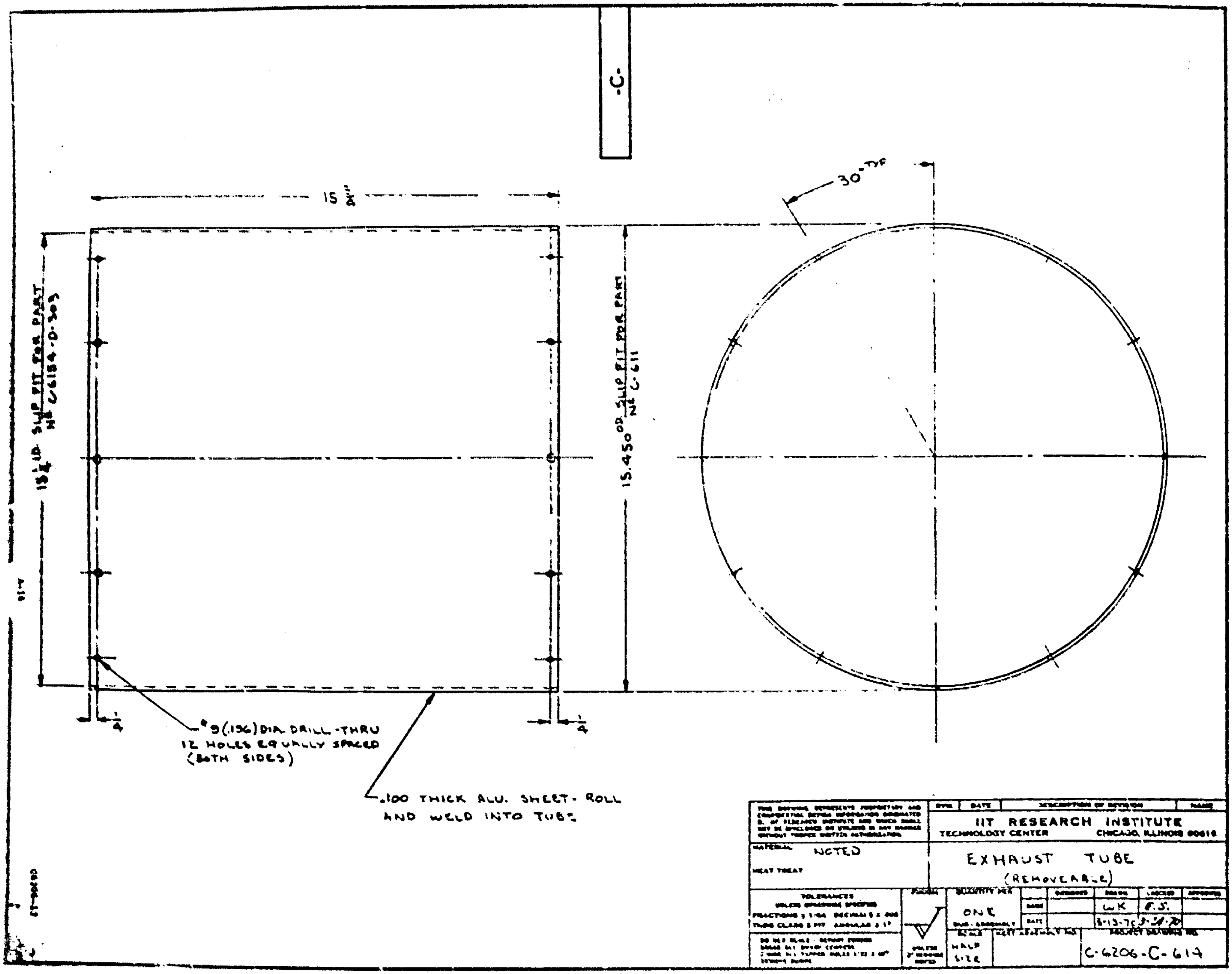
#10-32 TAP-THRU -24 HOLES TRAN: FROM TUBES #C-612, C-613, C-614, & C-615
.250 REF
15 7/8 DIA.
18.2 SLIP FIT FOR PART #C-612 AND C-613
18 5/8 DIA.
SECTION A-A
-C-
15.450 OD SLIP FIT FOR PART #C-614 AND C-615
9.687 TYP
2 DIA DRILL-THRU 4 HOLES
3/4 TYP
3/8 TYP
15° REF
30° TYP
A
IIT RESEARCH INSTITUTE
TECHNOLOGY CENTER
CHICAGO, ILLINOIS 60616
RING
MATERIAL 1/4 WROUGHT ALUMINUM PLATE - TYPE 200
TWO
HALF SIZE
WK
R.J.
7-18-70
9-24-70
C-6206-C-611


-C-
$\frac{3}{16}$ (.156) DIA DRILL-THRU
12 HOLES EQUALLY SPACED
(BOTH SIDES)
18.000 I.D. - SLIP FIT FOR PART
C-6184-D-903
FOUR CUTOUTS
REQD $\frac{1}{4}$ DEEP
18.2 DIA - SLIP FIT FOR PART C-611
30°
15°
.100 THICK ALU. SHEET-ROLL
AND WELD INTO TUBE
$\frac{1}{4}$
$15\frac{3}{4}$
IIT RESEARCH INSTITUTE
TECHNOLOGY CENTER CHICAGO, ILLINOIS 60616
MATERIAL NOTED
HEAT TREAT
DUST COLLECTING TUBE
(REMOVEABLE)
TOLERANCES
QUANTITY PER ONE
SCALE HALF SIZE
C-6206-C-612

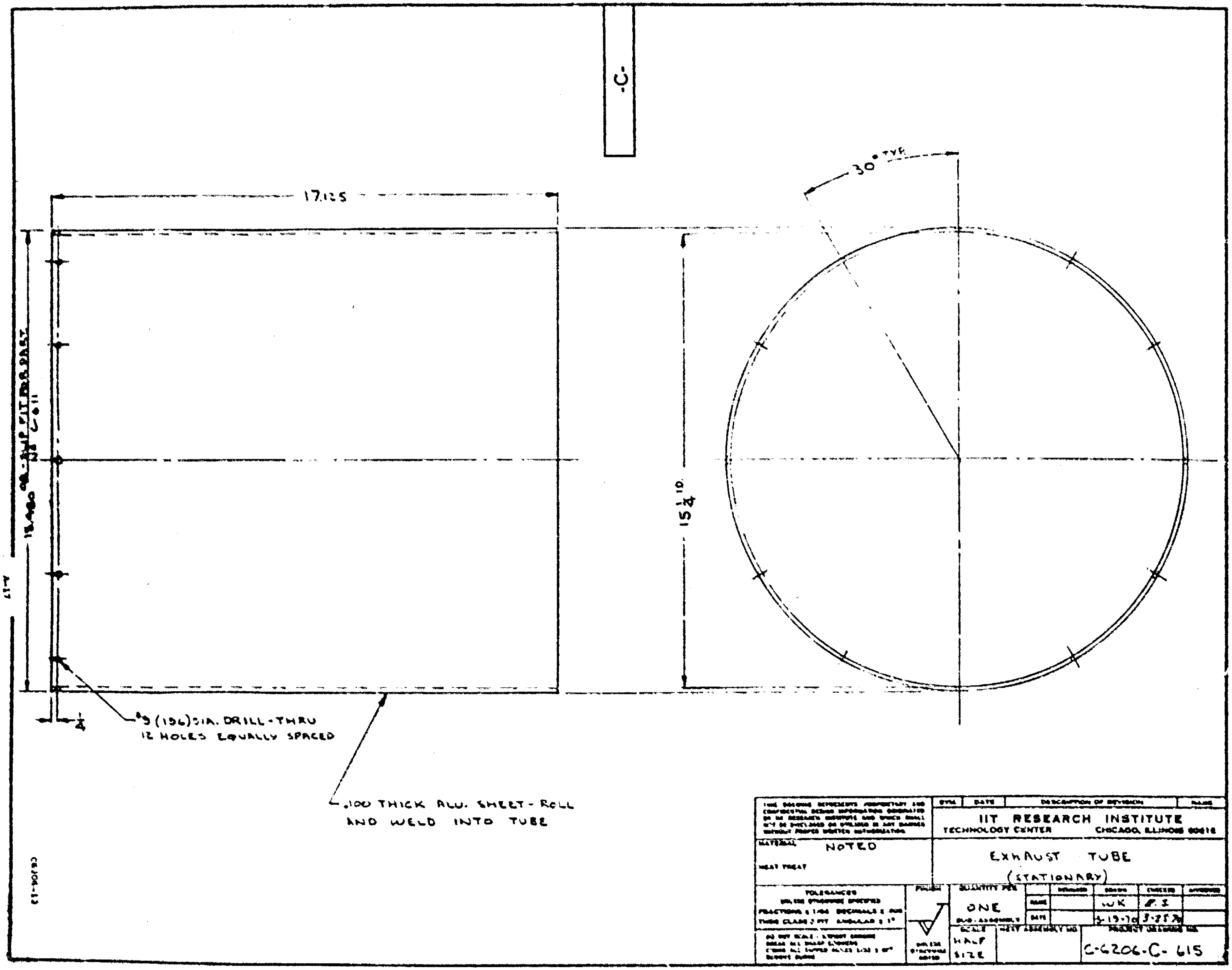
C6206-12


-C-
6
5 2/8
1/4
1/4
6
30° TYP
15°
℄ OF ∅ DRILL
75°
℄ OF CUTOUT
℄ CUTOUT
18.2 OD - SLIP FIT FOR PART NO C-611
18.000 DIA - SLIP FIT OVER PART # C-6154-D-402
FOUR CUTOUTS REQD. 1/4 DEEP
#9 (.196) DIA. DRILL THRU 12 HOLES EQUALLY SPACED - BOTH SIDES
13 1/8
.100 THICK ALU SHEET - ROLL AND WELD INTO TUBE
IIT RESEARCH INSTITUTE
TECHNOLOGY CENTER
CHICAGO, ILLINOIS 60616
MATERIAL NOTED
HEAT TREAT
DUST COLLECTING TUBE (STATIONARY)
QUANTITY PER ONE
WK
3-18-70
HALF SIZE
C-6206-C-613

C6204-12


-C-
15 3/4"
30° TYP
15 3/4 I.D. SLIP FIT FOR PART No. C6184-D-303
15.450 OD SLIP FIT FOR PART No. C-611
#9 (.156) DIA. DRILL-THRU
12 HOLES EQUALLY SPACED
(BOTH SIDES)
1/4
1/4
.100 THICK ALU. SHEET - ROLL
AND WELD INTO TUBE.
IIT RESEARCH INSTITUTE
TECHNOLOGY CENTER
CHICAGO, ILLINOIS 60616
MATERIAL NOTED
HEAT TREAT
EXHAUST TUBE
(REMOVEABLE)
TOLERANCES
QUANTITY REQ
ONE
SCALE
HALF SIZE
WK
E.S.
PROJECT DRAWING NO.
C-6206-C-614

C6206-13



-C-
30° TYP.
17.125
18.480 OD - SLIP FIT FOR PART No C-611
15 1/4 ID.
1/4
ø.3 (.156) DIA. DRILL-THRU
12 HOLES EQUALLY SPACED
.100 THICK ALU. SHEET - ROLL AND WELD INTO TUBE
IIT RESEARCH INSTITUTE
TECHNOLOGY CENTER CHICAGO, ILLINOIS 60616
MATERIAL NOTED
HEAT TREAT
EXHAUST TUBE (STATIONARY)
QUANTITY PER ONE
SUB-ASSEMBLY
SCALE HALF SIZE
NEXT ASSEMBLY NO.
PROJECT DRAWING NO. C-6206-C-615

C6J04-12

Appendix B

TEST PROCEDURE

TEST PROCEDURE

1. Install clean type E glass fiber filters in clean filter holders.

2. Check flow rate for both filters and mount in position with clean sampling probes, holes directed upstream; turn pumps off when through.

3. Weigh in dust for feeder.

4. Turn on big blower (main air flow) and measure Δp's for exhaust, brush and cyclone.

5. Turn on brush, low speed $\longrightarrow$ high speed and set for desired GPM (RPM) with big blower on. Measure pump pressure and GPM.

6. Turn on vacuum pump for filters.

7. Turn on dust feed (high rate) using 15 PSIG air (air on first) and leave on for measured time (usually 3 min.) using timers.

8. While dust is feeding measure Δp's for exhaust, brush and cyclone.

9. At proper time (usually 3 min.) shut off dust fedder mechanism and air supply and record dust feeding time interval.

10. Turn off vacuum pump for filters.

11. Turn off brush, high speed $\longrightarrow$ low speed $\longrightarrow$ off.

12. Turn off big blower.

13. Carefully disconnect sample probe from filter holder (so no dust is lost from either probe or filter holder) and check filter flow rates again - record.

14. Place filter in clean beaker or flask and add rinsings from sample probe. Dilute to fixed volume - say 100 cc.

15. Use B.C. green indicator, 1-2 drops 0.1%, and titrate to green color. Boil ca. 2-min, cool, (color will turn blue after Xs CO_2 is boiled off) and continue titration with 0.1N H_2SO_4 to green color. Record ml acid used. Also ml NaOH used if back titrated.

16. Prepare for next test.

SUPPLEMENTARY

INFORMATION

DEPARTMENT OF THE NAVY
NAVAL AIR SYSTEMS COMMAND
WASHINGTON, D. C. 20360

IN REPLY REFER TO

AIR-604A
1 March 1971

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To: Administrator
Defense Documentation Center For
Scientific and Technical Information
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(Mrs. Julia M. Lutz
Julia M. Lutz
BY DIRECTION

Errata

AD878848L